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FURTHER DEVELOPMENT OF OBJECTIVE METHODS FOR REGISTERING LANDMARKS AND DETERMINING CLOUD MOTIONS FROM SATELLITE DATA

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Prepared for:

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Scientific Report *September 1972*

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CONTENTS

ABSTRACT iii

LIST OF ILLUSTRATIONS vii

I INTRODUCTION 1

II MAJOR ELEMENTS OF THE AUTOMATIC SYSTEM 3

III LANDMARK MATCHING 7

IV BRIGHTNESS NORMALIZATION 17

V APPLICATION OF THE ISODATA AND MOTION PROGRAMS 19

A. Cloud Mass off the Brazilian Coast 22

B. Clouds off the African Coast 25

C. A Portion of the Intertropical Convergence Zone 25

VI PICTURE REGISTRATION, RECTIFICATION, AND GRIDDING 51

VII PRELIMINARY ESTIMATE OF FACILITIES AND COSTS 61

VIII SUMMARY 63

IX FURTHER RESEARCH 65

REFERENCES 67

DD Form 1473

ILLUSTRATIONS

1	The ATS-III Cloud Picture at 1620 GMT on 23 August 1969 (Designated as Tape S-5)	9
2	Computer Printout of Brightness Gradients for a Portion of Africa for Tapes S-5 and S-6	10
3	The Digital Brightness Values of Tape S-5 for the Landmark Template Indicated in Figure 2	11
4	A Map of RMS Brightness Differences Between the Landmark Template (Figure 3) and Tape S-6 at Different Locations on S-6	12
5	Computer Printout of Brightness Gradients for a Region Including Lake Titicaca (Bolivia) for Tapes S-5 and S-6 . .	13
6	The Digital Brightness Values of Tape S-5 for the Landmark of Figure 5	14
7	A Map of RMS Brightness Differences Between the Landmark Template (Figure 6) and Tape S-6	14
8	The Digital Brightness Values of Tape S-5 for a Landmark at the Southwest Corner of the Salar de Uyuni	15
9	A Map of RMS Brightness Differences Between the Landmark Template (Figure 8) and Tape S-6	16
10	Graph of Equivalent Brightness Values on Tape S-5 and Tape S-6 for a 250 by 500 Mile Portion of a Frontal Band . .	18
11	Representation of Brightness Values for a 250 by 500 Mile Region in the Atlantic off the Brazilian Coast at 1602 GMT, 24 June 1970 (Tape R-1)	27
12	Representation of Brightness Values for a 250 by 500 Mile Region in the Atlantic off the Brazilian Coast at 1628 GMT, 24 June 1970 (Tape R-2)	28

13	Computer Printout of the Brightest 300 Points of Figure 11 (Tape R-1)	29
14	Computer Printout of the Brightest 300 Points of Figure 12 (Tape R-2)	30
15	Computer Printout of Information About Groups from the ISODATA Program for the Data Shown in Figure 13	31
16	Computer Printout from ISODATA for Figure 14	32
17	Computer Printout of the Points of Figure 13 Along with Brightness Centers	33
18	Cloud Elements from Figure 14 and Brightness Centers	34
19	Brightness Centers on Two Consecutive Pictures	35
20	Computer Printout of Information from the MOTION Program	36
21	The Brightness Centers Matched in Pairs by the MOTION Program	37
22	A CRT Display of Brightness Data for a Portion of the Eastern Atlantic (Tape R-1)	38
23	A CRT Display of Brightness Data for a Portion of the Eastern Atlantic (Tape R-2)	39
24	Computer Printout of the 300 Brightest Elements from Figure 22 (Tape R-1) Along with Brightness Centers Found by ISODATA	40
25	Computer Printout of the 300 Brightest Elements from Figure 23 (Tape R-2) Along with Brightness Centers Found by ISODATA	41
26	The Brightness Centers Matched in Pairs by the MOTION Program	42
27	Representation of the Brightness Values for a 250 by 500 Mile Portion of the ITCZ from Tape R-1	43

28 Representation of Brightness Values for a 250 by 500 Mile Portion of the ITCZ from Tape R-2 44

29 Computer Printout of the 300 Brightest Elements from Figure 27 (Tape R-1) Along with Brightness Centers Selected by ISODATA 45

30 Computer Printout of the 300 Brightest Elements from Figure 28 (Tape R-2) Along with Brightness Centers Selected by ISODATA 46

31 The Brightness Centers Matched in Pairs by the MOTION Program 47

32 Computer Printout of 300 Elements from Figure 27 (Tape R-1) in the Intermediate Brightness Range 61-75 Along with Brightness Centers Found by ISODATA 48

33 Computer Printout of Elements in the Brightness Range 61-75 from Figure 28 (Tape R-2) Along with Brightness Centers Found by ISODATA 49

34 The Brightness Centers Matched in Pairs by the MOTION Program 50

35 Hypothetical Landmarks (Squares) on Picture 56

I INTRODUCTION

This work is a continuation of that discussed earlier in FAMOS TR 8-71 (Endlich, Hall, Wolf, and Brain, 1971), and published recently in a summary version (Hall, Endlich, Wolf, and Brain, 1972). The ultimate goal of the research is to develop automatic methods for measuring cloud motions from digital brightness data, without human intervention. The objective of the research reported herein is to develop specific computer techniques leading to this goal. The determination of cloud motions using computers is also under investigation by Leese, Novak, and Clark (1971) and by Smith and Phillips (1972). In the procedure used by Leese, Novak, and Clark, a cloud pattern for a sizeable region is tracked en masse using a cross-correlation technique. The detailed structure of the cloud pattern and variable motions within it are ignored. The procedure of Smith and Phillips keeps a man in the system to select tracer clouds, and then measures their motion, also by cross-correlation. Our system selects tracers (brightness centers) automatically, and matches them on successive pictures to obtain a smooth but variable field of displacements. Comparisons of these systems by applying them to a common set of data are needed.

The first part of the present report contains further tests of objective methods (embodied in programs DISK and MATCH) for registering landmarks on ATS-III pictures. A major portion of the study is concerned with the determination of cloud motions for the "R series" of tapes (for 24 June 1970) by using the ISODATA and MOTION programs. These programs were tested and improved using data for a variety of regions chosen to encompass different cloud types. The results are

quite satisfactory. The next portion of the report describes the new computer program CORRECT, which maps points from one picture onto another by use of information from the landmark registration program (MATCH). It makes corrections for translation, rotation, X-stretching, and Y-stretching. It also contains routines to transform any point from tape coordinates (columns X, and records Y) to earth coordinates (latitude and longitude), or the reverse. In the next part of the report, an initial estimate is given of the costs of cloud motion determination using this system. Further developments needed to assemble an objective, operational system are described in the final section.

II MAJOR ELEMENTS OF THE AUTOMATIC SYSTEM

The computer programs are still undergoing testing, and considerable additions and changes are anticipated to make them operational. The steps in the process as presently formulated are the following:

(1) Register picture 1 and picture 2 in (X, Y) coordinates

  (a) Match the earth's disk using chords (program DISK)

  (b) Match landmarks using templates (program MATCH), giving a correction for translation of picture 2 with respect to picture 1

(2) Select a region of picture 1 and the same region of picture 2 allowing for translation as above (program CLOUD)

(3) Perform brightness (Z) normalization (program NORMALIZE)

  (a) Compute cumulative brightness frequencies for the region

  (b) Normalize the second picture brightness to the first one

(4) Locate brightness centers (tracers)

  (a) For the region, set brightness thresholds to eliminate background (i.e., ground, sea)

  (b) Delete isolated (single) points

  (c) Apply ISODATA to get groups and their centers

    - Test for different scales and sizes of groups

    - Test different strategies for accuracy and speed of computation

(5) Compute cloud motions in (X, Y, Z) coordinates (program MOTION)

(a) Match brightness centers from picture 1 and picture 2 in pairs, to get a smooth field of motion and to minimize changes in the brightness, size, and shape of paired groups

(b) Delete centers without mates (i.e., matches

(6) Perform final registration and transformation to earth coordinates (program CORRECT)

(a) By using three or more landmarks in (X, Y) coordinates, correct picture 2 to picture 1 using rotation, X-stretching, and Y-stretching

(b) Using the landmark locations on an ideal picture, determine coefficients in equations that map any point of picture 1 onto the ideal picture

(c) Convert the ideal (X, Y) coordinates of cloud motion vectors to speed and direction, latitude and longitude.

The programs DISK and MATCH are described in the references given earlier. Since then only minor changes have been made to them. When the satellite's orbit and attitude are relatively stable, the earth's image is relatively fixed in the picture frame and the program DISK may not be needed. The program CLOUD selects data for a desired region to be used in the other programs. The ATS-III data on tape has 8192 samples o on each of 2400 lines. Three consecutive samples are averaged for each column so that an approximately square element is obtained. The size of the region is usually selected to be 50 lines by 100 columns or 100 lines by 200 columns. For the smaller area the brightness data on a 256-level gray scale pertain to elemental areas approximately 2.5 miles square when looking near the center of the picture. For the larger area, four adjacent data elements are averaged to reduce later computations of cloud motions, giving a brightness element approximately 5 miles square. Use of the latter averaged data in cloud tracking appears to give only a negligible loss of accuracy. (In landmark matching the higher resolution data are used.) The program NORMALIZE corrects for changes in illumination that occur in a region as the solar zenith angle varies with time

of day. The ISODATA program and some initial applications were described previously (Ball and Hall, 1967; Endlich, Wolf, Hall, and Brain, 1971). It locates centers of brightness for groups of points. These centers are used as tracers of cloud motions, analogous to the use of centers of gravity to trace motions in mechanical systems. ISODATA also reduces the original voluminous data to a much smaller set that contains the essential information concerning tracer elements. The MOTION program matches the brightness centers of two consecutive pictures to obtain a rather uniform field of motion. The matching of brightness centers considers the number of points, average brightness, and shape of groups, and checks for consistency of these factors. Also, it allows for the formation of new centers or the disappearance of old ones, and in this way accounts for the complex developmental aspects of clouds. The program CORRECT uses landmark information to register two successive pictures. Also, by using the latitude and longitude of landmarks and the concept of an ideal picture, it transforms the cloud locations and motions to earth coordinates (latitude and longitude, cloud speed and direction). The latitude and longitude of landmarks are identified visually by comparing digital data printouts (in an appropriate form) to standard maps. This simple visual matching is the only act in this series of operations that requires human intervention. At present it must be performed whenever the satellite subpoint is changed significantly.

For convenience and economy during development, the programs are presently broken into several groups; however, the final system that is envisioned will operate in a continuous sequence.

III LANDMARK MATCHING

In FAMOS TR 8-71, experiments were described that used ATS-III tapes for 24 June 1970, a series selected for us by Detachment FAMOS. This we call the "R series." It was found that DISK matching led to significant adjustments (on the order of 15 picture elements) between pictures 25 minutes apart. After DISK matching was performed, only minor changes of a few rows or columns were computed by the MATCH program to register selected landmarks. This indicated that internal differences between these particular pictures (in X, Y coordinates) were quite small. If this result proves to be generally true, many facets of the computer determination of cloud motions will be considerably simplified.

During the present study an improvement has been made to the MATCH program to ensure that it makes an exhaustive search in the area of best fit of a landmark template, and reaches the point of best agreement. Also, experiments were carried out using brightness gradients in matching in place of the original digital brightness. The gradient at a point is computed as the sum of the absolute value of a northeast-southwest brightness difference and an absolute value of northwest-southeast difference. The gradients tend to be relatively large along coastlines, and therefore, we thought that they might aid in landmark matching. However, in actual tests no mathematical advantage was found using gradients instead of the original digital brightness values. On the other hand, special printouts of the gradients were found to aid in visually checking the results of computer matches, and the gradients have been retained for this purpose.

A second series of tapes denoted "S" (for 23 August 1969) has been treated to a limited extent in the present study. For these, both DISK and MATCH adjustments are quite small, evidently because the satellite's attitude and orbit were nearly ideal. Some typical matches are illustrated below.

Figure 1 shows the ATS-III picture for 1620 GMT on 23 August 1969. This is the fifth picture of the daily sequence and is designated S-5. The picture was produced from tape on a facsimile recorder, with every 100th line and 300th column identified as an aid in visually checking computer results described later. Figure 2 shows a printout of gradients of digital brightness for a portion of the coast of northwest Africa. The coastline runs from upper right to lower left in each half of Figure 2. The left-hand part of the figure is for S-5, and the right-hand portion is for the next picture S-6 at 1645 GMT. The pictures have been adjusted to a first approximation for translation as indicated by the program DISK. In this case the DISK adjustment was only one row and one column. Small magnitudes of gradients (mainly over the ocean) are not printed in the figure. Large gradients exist at the coast and also along the edges of clouds. Where a brightness value exceeds a certain threshold (here chosen as 55) the gradient is not computed and a star is printed. This computer printout has the important role of facilitating visual inspection of computer landmark matching during the research process. The brightness values in the second picture (S6) were normalized to the levels in the first picture (S5) using the method described in Chapter IV.

The location of a landmark template (20 by 20 brightness values) is enclosed by lines in Figure 2. The brightness values for this template are shown in Figure 3. From Figure 2, one can see that the coast in S-5 is displaced downward and slightly to the left on tape S-6. The computer program MATCH makes the same decision (one row down and one column to the left), as indicated in Figure 4. This figure shows the "distances" (RMS differences in brightness) between the template (from

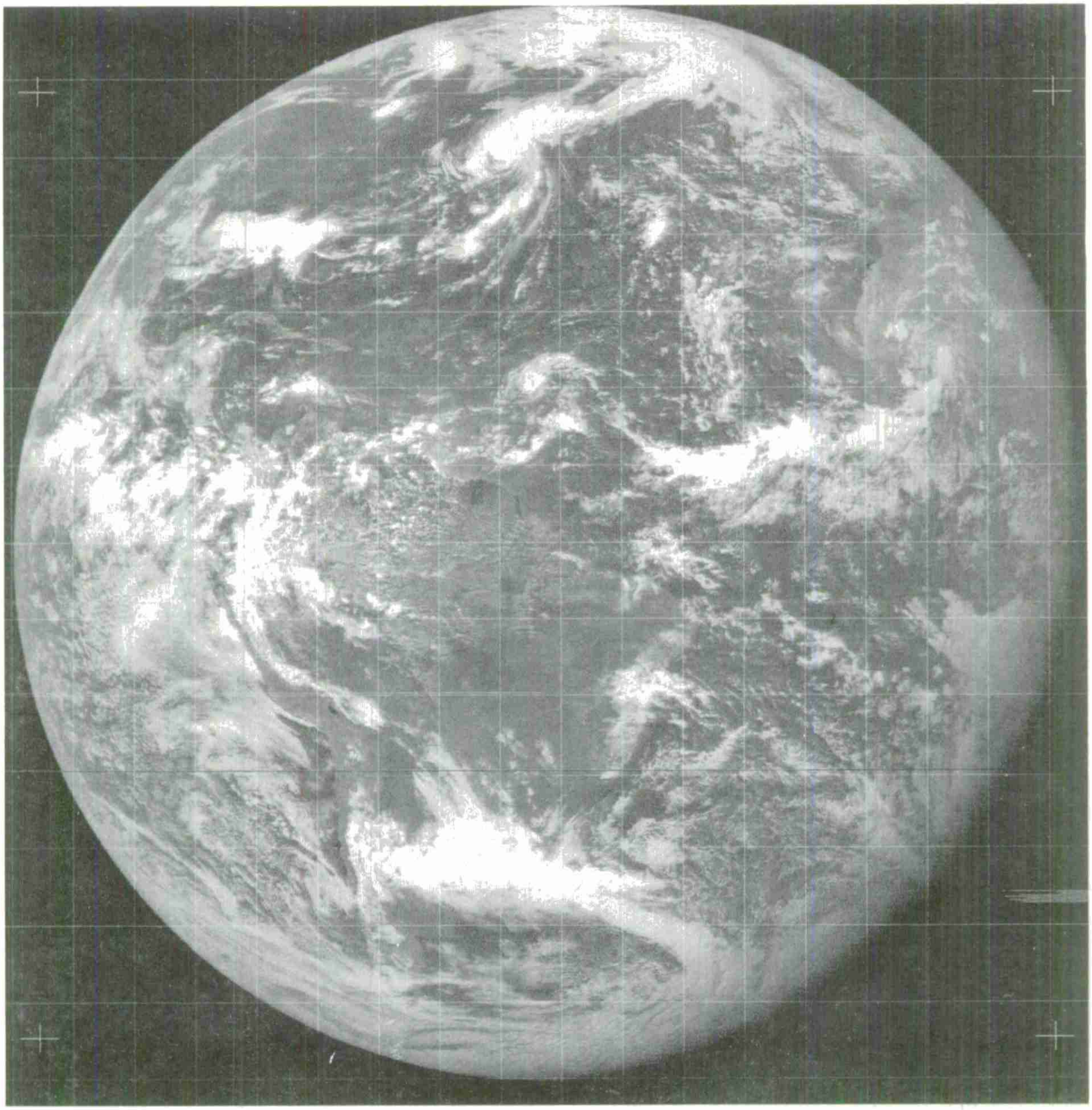

FIGURE 1 THE ATS-III CLOUD PICTURE AT 1620 GMT ON 23 AUGUST 1969 (DESIGNATED AS TAPE S-5). Horizontal lines are at increments of 167 records. Vertical lines are at increments of 400 brightness elements within records.

FIGURE 2 COMPUTER PRINTOUT OF BRIGHTNESS GRADIENTS FOR A PORTION OF AFRICA FOR TAPES S-5 (LEFT) AND S-6 (RIGHT). The coast runs from upper right to lower left. The location of a landmark template on S-5 is enclosed by lines.

AFRICA-2 S5-S6 S6 ADJUSTED TO S5
KEYX= 20 KEYY= 20 MAXXT= 20 MAXYT= 20, NPIC= 2

TEMPLATE:

33	30	29	31	30	31	26	30	28	32	28	26	28	27	25	27	26	30	29	24
28	33	30	31	31	33	28	28	26	27	33	27	26	25	25	28	26	30	23	29
25	27	27	25	30	25	28	25	26	29	24	26	25	25	26	25	22	21	23	27
26	27	29	30	22	20	24	27	26	22	27	27	30	27	24	24	30	29	27	25
27	23	30	24	26	32	28	33	22	20	24	27	24	30	25	26	25	27	28	27
28	25	28	24	25	25	32	22	26	20	23	26	27	30	25	28	28	24	30	37
26	29	26	28	30	25	29	20	30	26	28	33	35	38	43	50	51	52	48	56
26	26	28	28	24	25	26	32	46	53	56	58	59	58	55	59	57	55	58	53
26	24	26	26	25	24	25	33	43	48	55	55	54	57	63	55	50	55	61	56
26	27	26	29	27	25	26	27	45	52	55	55	55	47	53	58	51	53	50	56
26	26	29	26	26	28	28	37	46	53	54	52	45	47	52	53	49	57	48	55
27	26	26	25	24	24	40	47	48	54	56	50	53	54	52	58	53	58	55	52
29	32	31	32	27	26	41	52	55	49	64	53	58	53	52	53	50	49	52	51
29	27	27	29	31	27	41	52	50	50	56	59	61	60	55	50	51	58	53	51
27	26	25	23	31	24	36	47	53	57	63	62	63	62	57	58	56	57	61	61
24	28	31	29	32	25	34	48	50	48	61	58	57	59	55	54	53	52	56	52
29	29	25	29	30	25	34	56	47	59	62	65	63	56	61	52	54	54	55	55
25	27	28	27	28	30	37	50	49	55	51	63	61	58	60	54	51	53	56	54
27	27	27	26	28	27	37	48	50	53	50	53	55	55	59	48	58	55	55	52
27	25	26	28	32	23	40	48	48	51	53	55	53	54	54	50	50	47	55	50

FIGURE 3 THE DIGITAL BRIGHTNESS VALUES OF TAPE S-5 FOR THE LANDMARK TEMPLATE INDICATED IN FIGURE 2

the first tape) and the brightness values of the second tape at different positions. The best match (least distance) is 4.68, which is considerably better than at the surrounding points. Therefore we have confidence in this result. (The number 80.58 is inserted at points for which no calculation was made.)

It is also worth noting that the upper left-hand part of the landmark rectangle in Figure 2 contains a cloud edge. We have not found a way to completely eliminate interference from clouds in the matching process. As described in FAMOS TR 8-71, for most landmarks their influence is minimized by ignoring points brighter than a given level (such as 55) typical of clouds. This strategy appears to be generally satisfactory.

We next show a landmark for a portion of the northern part of Lake Titicaca in Bolivia, easily discernible in Figure 1. The gradients for tapes S-5 and S-6 are shown in Figure 5. An approximate outline of the lake has been sketched to facilitate inspection. The landmark template on picture S-5 is enclosed by lines and the digital brightness is given in Figure 6. From Figure 5, the eye can detect a relative displacement

	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	
12	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	12
13	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	13
14	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	14
15	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	12.63	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	15
16	*80.58	16.17	*80.58	*80.58	*80.58	*80.58	13.26	*80.58	*80.58	*80.58	11.48	11.62	12.03	*80.58	*80.58	*80.58	13.52	*80.58	*80.58	16
17	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	10.52	10.80	11.31	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	17
18	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	9.69	10.13	10.74	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	18
19	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	9.33	8.61	8.22	8.78	9.21	10.14	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	19
20	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	9.29	8.04	6.90	6.04	7.19	8.25	9.59	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	20
21	*80.58	14.14	*80.58	*80.58	*80.58	9.46	7.94	6.32	4.80	$\boxed{4.08}$	6.13	7.42	9.69	*80.58	*80.58	*80.58	15.27	*80.58	*80.58	21
22	*80.58	*80.58	*80.58	*80.58	*80.58	8.87	7.49	6.03	5.05	5.61	7.50	9.15	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	22
23	*80.58	*80.58	*80.58	*80.58	*80.58	9.63	8.50	7.58	7.02	7.75	9.26	10.79	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	23
24	*80.58	*80.58	*80.58	*80.58	*80.58	10.10	9.21	8.63	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	24
25	*80.58	*80.58	*80.58	*80.58	*80.58	10.70	10.25	9.80	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	25
26	*80.58	14.13	*80.58	*80.58	*80.58	11.51	11.13	11.01	*80.58	*80.58	*80.58	14.87	*80.58	*80.58	*80.58	*80.58	21.71	*80.58	*80.58	26
27	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	12.18	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	27
28	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	28
29	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	29
30	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	30
	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	

MINIMUM VALUE = 4.083, AT 19 21

AFRICA-2 S5-S6 S5 ADJUSTED TO S6
TRANSLATION VECTOR FOR AFRICA-2 DELTA COL -2 DELTA LINE 1 START AT (KEYX,KEYY) 20 20

FIGURE 4 A MAP OF RMS BRIGHTNESS DIFFERENCES BETWEEN THE LANDMARK TEMPLATE (FIGURE 3) AND TAPE S-6 AT DIFFERENT LOCATIONS ON S-6. The minimum difference (best fit) is enclosed by a rectangle. The template (referenced at 20,20 on S-5) fits best at 19,21 on S-6.

FIGURE 5 COMPUTER PRINTOUT OF BRIGHTNESS GRADIENTS FOR A REGION INCLUDING LAKE TITICACA (BOLIVIA) FOR TAPES S-5 (LEFT) AND S-6 (RIGHT). The approximate outline of the lake, and the location of a landmark template are indicated.

TEMPLATE:

43	49	42	43	45	46	37	41	34	45	45	41	42	45	41	37	33	42	38	43
47	51	47	41	36	37	43	39	41	44	41	45	39	36	43	41	45	34	36	39
42	44	43	29	23	28	10	36	38	44	38	37	41	36	38	39	40	48	40	37
44	47	40	44	46	43	36	33	40	43	44	40	42	39	40	39	42	40	40	41
47	42	44	45	49	47	52	49	45	47	44	32	37	39	38	40	42	38	37	36
39	43	45	46	50	46	46	42	44	40	42	32	25	38	36	39	34	39	42	36
41	41	44	46	50	46	41	48	56	36	30	23	25	27	37	33	38	39	40	40
38	42	43	50	44	38	41	49	44	23	22	20	17	20	20	26	25	38	35	40
44	44	42	42	45	39	41	37	28	29	24	16	17	15	13	16	23	33	31	35
44	40	45	44	44	39	37	39	27	20	19	22	17	18	15	12	13	17	30	30
41	43	44	42	43	41	43	44	41	23	20	23	22	13	15	14	14	10	19	25
45	40	45	43	46	46	48	41	41	33	22	24	18	15	17	10	12	15	14	11
47	42	44	45	42	49	48	46	38	33	36	24	17	17	16	15	20	18	12	17
34	42	45	46	44	40	50	56	49	34	36	24	22	19	17	17	13	14	11	14
40	45	42	41	43	43	48	52	43	31	31	29	21	20	19	17	15	17	18	20
41	40	43	32	40	44	46	30	25	21	20	19	17	20	15	15	14	17	15	12
37	41	44	44	39	34	40	30	30	25	23	23	19	19	18	20	17	17	12	14
34	41	39	47	38	39	36	30	23	18	30	36	19	17	14	19	16	16	16	15
37	43	38	35	34	32	35	38	33	34	25	30	21	21	16	17	14	10	16	15
37	30	38	32	36	42	36	41	34	41	38	49	39	35	26	22	18	15	17	18

FIGURE 6 THE DIGITAL BRIGHTNESS VALUES OF TAPE S-5 FOR THE LANDMARK OF FIGURE 5.

of the outline of the lake from S-5 to S-6, similar to that shown earlier for the African landmark. The computer match finds a minimum distance of 4.02, displaced 2 rows down and 1 column to the left of the original template position, as shown in Figure 7. Exactly the same displacement was computed using a second template that included the southern end of Lake Titicaca.

```
      10    11    12    13    14    15    16    17    18    19    20    21    22    23    24    25    26    27    28
13*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58
14*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58
15*80.58*80.58*80.58*80.58*80.58*80.58 10.90*80.58*80.58*80.58 11.42 12.05*80.58*80.58*80.58*80.58*80.58*80.58*80.58
16*80.58 13.75*80.58*80.58*80.58 11.27 10.71 10.53*80.58 10.61 11.11 11.60 12.47*80.58*80.58*80.58 17.07*80.58*80.58
17*80.58*80.58*80.58*80.58*80.58 11.02 10.41 10.20*80.58 10.08 10.51 11.14*80.58*80.58*80.58*80.58*80.58*80.58*80.58
18*80.58*80.58*80.58*80.58*80.58 10.78 10.17  9.88*80.58  9.54  9.97 10.64*80.58*80.58*80.58*80.58*80.58*80.58*80.58
19*80.58*80.58*80.58*80.58*80.58 10.06  9.36  8.84*80.58  8.55  8.90  9.74*80.58*80.58*80.58*80.58*80.58*80.58*80.58
20*80.58*80.58*80.58*80.58*80.58  9.72  8.82  7.98  7.27  7.46  7.94  8.87*80.58*80.58*80.58*80.58*80.58*80.58*80.58
21*80.58 13.18*80.58*80.58*80.58  9.59  8.23  7.09  5.83  5.67  6.62  7.81  9.36*80.58*80.58*80.58 15.74*80.58*80.58
22*80.58*80.58*80.58*80.58*80.58*80.58  8.47  7.06  5.39  4.02  5.47  7.27*80.58*80.58*80.58*80.58*80.58*80.58*80.58
23*80.58*80.58*80.58*80.58*80.58*80.58*80.58  8.53  7.41  6.61  6.83  7.89  8.90*80.58*80.58*80.58*80.58*80.58*80.58
24*80.58*80.58*80.58*80.58*80.58*80.58*80.58 10.10  9.47  9.10  8.84  9.05  9.66*80.58*80.58*80.58*80.58*80.58*80.58
25*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58 10.49 10.37 10.53*80.58*80.58*80.58*80.58*80.58*80.58
26*80.58 13.55*80.58*80.58*80.58*80.58 12.70*80.58*80.58*80.58 11.75 11.59 11.52*80.58*80.58*80.58 14.34*80.58*80.58
27*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58 12.34*80.58*80.58*80.58*80.58*80.58*80.58*80.58
28*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58
29*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58
30*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58*80.58
31*80.58 14.04*80.58*80.58*80.58*80.58 15.37*80.58*80.58*80.58*80.58 15.44*80.58*80.58*80.58*80.58 14.82*80.58*80.58
      10    11    12    13    14    15    16    17    18    19    20    21    22    23    24    25    26    27    28
MINIMUM VALUE =      4.018, AT  19 22


TITICACA N     55-56  56 ADJUSTED TO 55
TRANSLATION VECTOR FOR TITICACA N     DELTA COL -2     DELTA LINE  2          START AT (KEYX,KEYY)   20   20
```

FIGURE 7 A MAP OF RMS BRIGHTNESS DIFFERENCES BETWEEN THE LANDMARK TEMPLATE (FIGURE 6) AND TAPE S-6. The template (referenced at 20,20 on S-5) fits best at 19,22 on S-6.

One of the best landmarks in this part of the world is a large, bright, dry lake in Bolivia called Salar de Uyuni. The landmark template for a portion of this lake is shown in Figure 8. Some brightness values are as high as those found with bright clouds, so that a brightness cutoff (e.g., 55) is not used for this landmark. Very large brightness gradients exist in the template, much larger than those in Figure 3 and 6.

```
DRY LAKE1      55-56  S6 ADJUSTED TO 55
 KEYX=    20          KEYY=    20              MAXXT=    20          MAXYT=    20,  NP1C=  2
```

TEMPLATE:

53	49	48	47	48	43	60	97	112	128	125	132	136	146	148	161	165	163	160	168
46	50	43	48	49	44	50	87	108	122	117	138	143	145	139	140	154	151	148	154
55	50	40	51	48	50	55	79	113	114	126	140	129	143	143	147	160	160	157	144
57	52	47	47	53	53	54	63	91	122	129	143	148	148	142	140	149	151	150	142
51	49	50	54	64	53	47	74	115	128	133	151	142	135	138	147	139	146	148	156
52	52	51	72	62	52	55	78	122	126	147	144	144	140	146	136	145	151	150	154
49	67	67	94	59	55	57	91	120	136	137	139	129	97	121	135	148	140	145	159
54	90	127	129	74	64	72	120	131	142	150	114	98	80	99	118	137	136	139	138
53	81	84	80	58	54	61	100	123	131	150	146	124	82	96	111	139	146	151	138
67	88	93	72	53	48	54	89	117	134	132	151	124	84	96	124	146	129	129	158
63	89	91	74	58	50	49	70	109	123	126	101	89	63	71	118	138	125	92	126
49	69	67	59	58	46	46	59	102	108	116	136	111	70	68	120	134	125	76	80
48	49	51	45	47	46	47	50	79	92	96	103	88	58	68	98	94	103	60	59
71	52	51	49	52	53	49	47	55	51	41	42	44	60	84	85	76	61	55	47
73	60	54	83	69	53	59	50	42	45	48	42	38	49	74	82	70	54	48	48
56	58	73	93	79	64	55	43	47	38	38	37	39	43	66	72	57	49	41	44
59	54	70	65	67	56	53	44	46	44	41	42	42	55	59	63	51	52	41	42
71	66	77	75	60	61	48	47	42	42	41	42	51	63	74	62	53	47	41	39
67	77	105	99	80	69	63	59	47	52	49	44	45	50	74	61	45	48	39	48
111	82	117	139	112	87	80	65	63	57	62	61	58	46	51	60	58	46	45	55

FIGURE 8 THE DIGITAL BRIGHTNESS VALUES OF TAPE S-5 FOR A LANDMARK AT THE SOUTHWEST CORNER OF THE SALAR DE UYUNI

For this landmark the computer matching (Figure 9) gives a very clearly marked minimum displaced 2 rows down and 2 columns to the left of the original template position. The values of distance in Figure 8 have such a clear pattern that one could interpolate a fit to a location between the positions for which computations were made.

For the same pair of tapes, other landmarks were selected and matched with very similar results. One of these was along the north-east coast of Brazil. Here the brightness contrasts are relatively small, and cloud contamination is frequent, so the landmark is not highly reliable. Landmarks along the cost of Chile have fairly good brightness

	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
13	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58
14	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58
15	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58
16	*80.58	*80.58	46.34	*80.58	*80.58	*80.58	*80.58	45.81	*80.58	*80.58	*80.58	*80.58	52.21	*80.58	*80.58	*80.58	*80.58	62.35	*80.58
17	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58
18	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58
19	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58
20	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	27.29	22.63	21.66	26.28	32.17	37.14	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58
21	*80.58	*80.58	36.45	*80.58	*80.58	*80.58	30.05	24.33	16.17	13.52	20.98	28.66	33.93	36.90	*80.58	*80.58	*80.58	46.60	*80.58
22	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	23.91	13.56	7.27	18.31	26.80	31.68	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58
23	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	28.19	19.38	16.26	21.04	27.33	31.13	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58
24	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	28.55	24.26	23.42	26.19	29.87	32.22	32.69	*80.58	*80.58	*80.58	*80.58	*80.58
25	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	35.63	31.33	28.10	28.14	30.48	32.68	33.86	33.63	*80.58	*80.58	*80.58	*80.58	*80.58
26	*80.58	*80.58	44.28	*80.58	*80.58	*80.58	38.01	34.88	32.80	*80.58	*80.58	35.32	35.36	34.71	*80.58	*80.58	*80.58	36.69	*80.58
27	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	38.18	*80.58	*80.58	*80.58	*80.58	37.11	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58
28	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58
29	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58
30	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58	*80.58
31	*80.58	*80.58	49.47	*80.58	*80.58	*80.58	48.34	*80.58	*80.58	*80.58	*80.58	*80.58	43.91	*80.58	*80.58	*80.58	*80.58	39.61	*80.58
	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27

MINIMUM VALUE = 7.269, AT 18 22

DRY LAKE1 55-56 56 ADJUSTED TO 55
TRANSLATION VECTOR FOR DRY LAKE1 DELTA COL -2 DELTA LINE 2 START AT (KEYX,KEYY) 20 20

FIGURE 9 A MAP OF RMS BRIGHTNESS DIFFERENCES BETWEEN THE LANDMARK TEMPLATE (FIGURE 8) AND TAPE S-6. The template (referenced at 20,20 on S-5) fits best at 18,22 on S-6.

constrasts, but are expected to be cloud covered on many occasions. In the present case, a Chilean landmark (at 29°S) was displaced two rows down and two columns to the left on picture S-6 compared to S-5, and an Argentine coastal landmark (at 35°S) was displaced three rows down and one column to the left.

Experiments of this sort show that automatic landmark matching can be done for a variety of landmarks. For some of them (e.g., Figure 7) the pattern of fit is rather flat in the vicinity of the best match, so that fitting to one picture element is near the limit of accuracy that can be achieved. On the other hand, for a very sharply defined landmark (such as that of Figure 8), interpolative matching finer than a picture element appears feasible. It is also important to note that the landmark displacements in different parts of the picture are nearly the same, indicating that internal distortions are small for this sequence of tapes.

IV BRIGHTNESS NORMALIZATION

At a given place the sun's illumination is, of course, a maximum at local noon. During the middle of the day changes in illumination from picture to picture are relatively slight, but they are quite significant in the early morning or late afternoon. The simplest assumption that one can make about brightness is that it will vary directly with the secant of the solar zenith angle. Some of the brightness data we have examined indicate that the relationships are actually more complex. Therefore an empirical correction is made by the program NORMALIZE. It is assumed that the cloud population in a region several hundred miles on a side remains unchanged from one picture to the next, even though random variations may occur in individual cloud elements. With this assumption, histograms of brightness at the two times would be the same except for changes in illumination. Cumulative histograms are computed for picture 1 and picture 2. For example, for a 250 by 500 mile portion of a frontal band in the mid-Atlantic, picture 2 has 303 points (out of 5000) having brightness ≥ 70, while in picture 1, there are 330 such elements. We wish to find the brightness level on picture 1 which has 303 elements of equal or greater brightness, and find from the histogram that the level 72 on picture 1 meets this criterion. Therefore the level 70 on picture 2 corresponds to the level 72 on picture 1. Similar computations made by the subroutine NORMALIZE give the corresponding brightness levels shown in Figure 10. The dashed line would imply perfect agreement. Deviations from perfect agreement are, of course, greatest for picture pairs in early morning or late afternoon. In such cases the normalization is important, particularly if landmark matching is to be done in the region. For picture pairs near local noon (as in

Figure 10), brightness normalization is probably not needed. In the present system, brightness normalization is done routinely prior to use of the ISODATA program; however, a criterion to use it selectively will be introduced in further work.

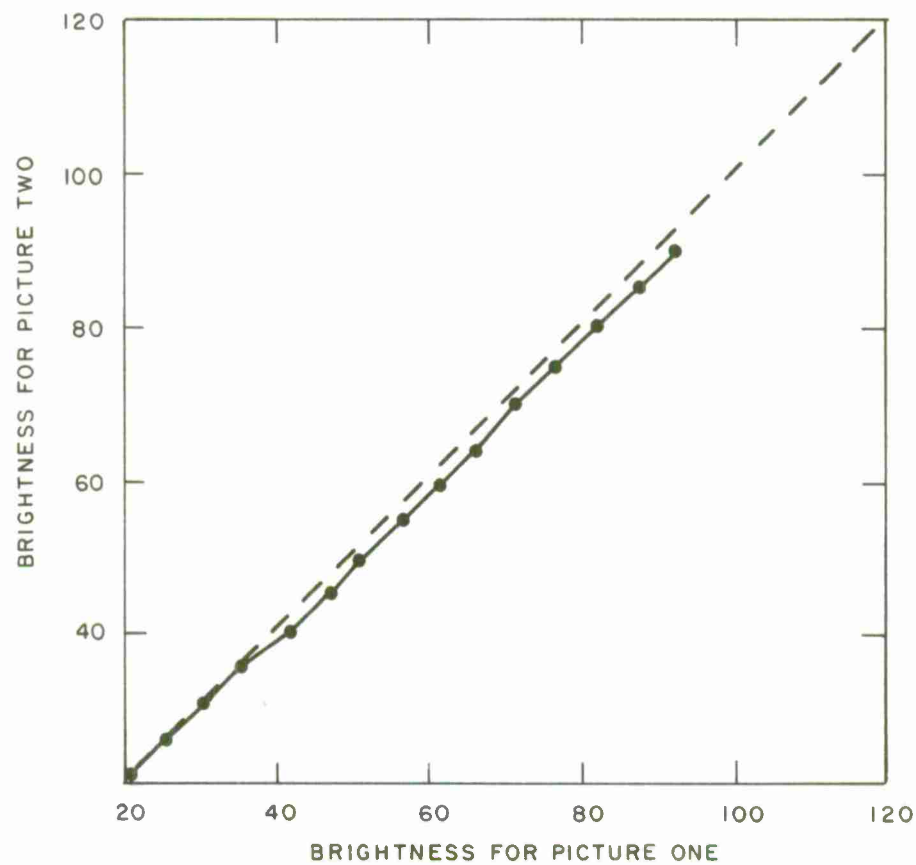

FIGURE 10 GRAPH OF EQUIVALENT BRIGHTNESS VALUES ON TAPE S-5 (PICTURE 1) AND TAPE S-6 (PICTURE 2) FOR A 250 BY 500 MILE PORTION OF A FRONTAL BAND

V APPLICATION OF THE ISODATA AND MOTION PROGRAMS

The ISODATA program (Ball and Hall, 1967) performs two basic functions. Firstly, it gives a major compaction in the amount of data needed for the present purpose, and secondly, it selects brightness centers for use as tracers (Endlich, Hall, Wolf, and Brain, 1971). The centers are analogous to the cloud centroids identified by eye by Shenk and Kriens (1970). ISODATA subdivides a data set into "natural" groups, and then computes the group center and group shape parameters (standard deviations in X and Y direction, skewness, and kurtosis of brightness). These few statistics describe the groups quite adequately. Input parameters to ISODATA exert control over the approximate number of centers desired, the typical distance between them, or the rms distance of points from their centers. The centers found on one picture are used as initial guesses in applying ISODATA to the second picture. In this case ISODATA shifts the brightness centers to their new positions of best fit. The difference between the coordinates of the brightness centers in the two pictures is a measure of the displacement of the centers. These displacements may be transformed into earth distances and divided by the time interval between pictures to give the motion vectors of the brightness centers representing the clouds. With this approach, the motions of centers will be representative of the average motion of the cloud elements that belong to the group.

In the present study, the following strategy for using ISODATA was formulated empirically. Two control parameters are furnished as input. One of these is a search radius that tends to control the initial size of groups. A relatively large search radius gives a small number of large groups, and conversely. The second control parameter is called

θ_c, the splitting parameter. During each iteration, ISODATA selects the most elongated group and makes a trial splitting of it into two subgroups. If the new subgroup centers are more than the distance θ_c apart the splitting is retained; otherwise the original group is saved. Thus the search and splitting operations of ISODATA are used to define groups, without use of other options in the ISODATA program. Usually three to six iterations give stable results. In many of the present runs, satisfactory results have been obtained by setting the search radius equal to 20 units of X (or Y), and θ_c equal to 10. The resulting cloud motions are not affected significantly by varying these parameters by a factor of 2.

In using ISODATA, the computations increase with the number of points, and therefore it is desirable to keep the number of points fairly low. A number of approximately 300 gives a rapid computation. If there are extensive clouds in the region being treated, 300 brightness values are inadequate to describe the total pattern. In this case it may be desirable to subdivide (or slice) the data, first taking the brightest 300 points, then the next brightest 300, etc., until background values are encountered. This is only an interim procedure, while more powerful alternatives are being formulated.

Another step in treating the data for use by ISODATA is the deletion of isolated points from the data arrays, i.e., a point bright enough to be considered as cloud, but having no adjacent neighbors, is deleted. This tends to remove small, changeable features that would often be noise in the groupings made by ISODATA.

The use of the brightness centers found on the first picture of a pair as first-guess centers on the second picture speeds up the ISODATA computation on the second picture, and also tends to ensure continuity of the centers.

As mentioned earlier, centers of brightness determined by ISODATA in two photographs separated in time by an appropriate amount must be matched so that the displacement of a center can be computed from its change in coordinates. In doing this, one encounters a practical difficulty because a cloud group and its brightness center may appear on one picture of a pair, but not the other. This can occur because of formation or dissipation of a cloud group, or movement of a group across a boundary of the digitized area. For this reason, there may not be mates for all the brightness centers, and pair matching may be confused. The MOTION program copes with this problem under most circumstances. It matches those pairs that are "good" mates and discards those centers that do not have a mate.

At present the matching of brightness centers by the MOTION program is based on the following factors: the expected motion vector for the region (if known), the number of points in groups, the average brightness of groups, and the shape of groups. If there is no previous knowledge, the initial matching looks for a motion of zero, which is equivalent to looking for nearest neighbors in matching centers at times 1 and 2. In addition, the matching associates groups having the same size, brightness, and shape. In practice, weights must be assigned to the various factors to specify their relative importance. So far this assignment has been done on a purely empirical basis, in a manner that gives acceptable results for a variety of cases.

After the initial matching, the motion components ΔX and ΔY for each matched pair of brightness centers are computed, and the average ΔX and ΔY for the region are found. The matching process is then repeated, with these averages used to define the expected positions of pairs. Generally, the pair matching will be changed from that of the initial iteration, so that a somewhat different field of motion is obtained. This field-of-motion vectors tends to be in agreement with the

average, and this introduces uniformity over the region. The process is repeated until the results become stable. Usually this requires no more than four iterations.

These concepts, which are difficult to grasp in abstract discussion, are now illustrated with several examples based on the R-series of tapes.

A. Cloud Mass off the Brazilian Coast

The digital brightness data for this area for tape R-1 (corresponding to 1602 GMT) are shown in Figure 11(a).* Each digit represents the average brightness in a 5 by 5 mile element (approximately), computed by averaging the original values of four 2.5 by 2.5 mile elements. The 50 by 100 array therefore covers a region of approximately 250 by 500 miles. For this presentation, the digits are scaled so that a 1 represents brightness in the range 10 to 19, 2 represents 20-29, and so on, then using the alphabet for brightness > 100. The ocean background consists mainly of 1's. To see exactly the same data in a more familiar pictorial form, a display on the computer controlled cathoderay-tube (CRT) display was made using 10 levels of shading as shown in Figure 11(b). The divisions between shades may be set arbitrarily. We have set them in a simple manner; however, by judicious choice, one could use this selectivity to enhance certain cloud features for inspection.

The brightness data for the same region of tape R-2 (at 1628 GMT) corrected for translation are shown in Figure 12(a), and the CRT picture is also illustrated. The patterns are of course very similar to those of Figure 11 in broad features.

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* Figures are shown at the end of this section, p. 27.

As mentioned earlier, it has been convenient so far for ISODATA to operate on approximately 300 data points. Therefore the data are scanned beginning with the brightest, and points are saved for successively smaller brightness values until the number of points exceeds 300. The resulting subset from Figure 11 is shown in Figure 13. A similar subset from Figure 12 (26 minutes later) is shown in Figure 14.

Part of the printout of information about the 16 groups selected by ISODATA is shown in Figure 15. For example, the first group, consisting of 33 points (or patterns), is centered at X = 239.82, Y = 45.45, and has an average brightness of 98.61. Similarly, Figure 16 is a printout for the second picture, which is divided into 17 groups. The information is shown graphically for the two times in Figures 17 and 18 with dots marking data points and C's marking X and Y locations of group centers. (The C's frequently overlie data points.) Points belong to the nearest group center. The ISODATA computations were made with the search radius (sphere factor) equal to 20, and the splitting distance θ_c equal to 10. Here one can see how ISODATA distributes centers in a typical amorphous cloud pattern. As mentioned earlier, the brightness centers of the first picture (Figure 17) are used as a first guess in operating on the second one (Figure 18). In this case, the leftmost group in Figure 17 is changed somewhat in Figure 18, and is divided into two groups, giving an additional center. However, all of the other 15 centers in Figure 17 have counterparts in Figure 18. It should also be realized that if different values of the search radius and splitting distance had been used, a different set of centers would have been obtained. By choosing smaller values for them, one would obtain more centers, and therefore more motion vectors. The setting of these controls is made empirically to meet the intended analysis resolution.

To illustrate the problem of matching centers, refer to Figure 19. Here the 1's are the first centers (from Figure 20), and the 2's are the

second set (from Figure 18), while 3's denote 1's and 2's superposed because of the inability of the line printer to resolve them when they are close together. As mentioned earlier, the matching process looks for an expected vector difference (which may be set to zero initially), and also pairs groups having similar characteristics. A key computation in the computer matching involves the "fitting factor," which compares each center of picture 1 to each center of picture 2. For the present case, this matrix is shown in the upper part of Figure 20. The best fit, the value 4.6 enclosed by a rectangle, is between center 3 on picture 1 and center 3 on picture 2. The lower part of Figure 20 shows the matched pairs in order, designated by letters of the alphabet. The first pair (A) implies a cloud motion having components in the X and Y directions of -3.7 and 0.1 units. (The conversion of these units to earth coordinates is discussed in Section VI. For this particular area, the components should be multiplied by 6, approximately, to obtain cloud motions in knots.) The midpoint of the motion vector A is at X = 281.0 and Y = 25.1, and the average brightness of the two centers is 88.2. Other information is also given for purposes of monitoring the decisions made by the program.

The 12 matched pairs are shown graphically in Figurc 21 along with their identifying letters. The motions go from 1's to 2's, whereas 3's imply motions of approximately zero. Centers which do not have an accompanying letter are not matched, even though a line connecting them may appear reasonable to the eye. This is because rejection can occur due to changes in size of a group (marked growth or decay), complications due to movements across the edges of a region, changes in shape or brightness, or motion quite different from the average motion of the other matched pairs. In practice, rejection is made by rating each vector, and comparing the rating to a critical value. In Figure 20 this critical value is set at 10, and pairs having larger values (poorer matches) are

rejected. These ratings are given in the column marked FIT. In general, we believe it is desirable to eliminate most of the doubtful matches, so that those retained are meteorologically acceptable. One method of determining meteorological acceptability will be to examine the same cases visually using the SRI electronic cloud console. This task remains to be done.

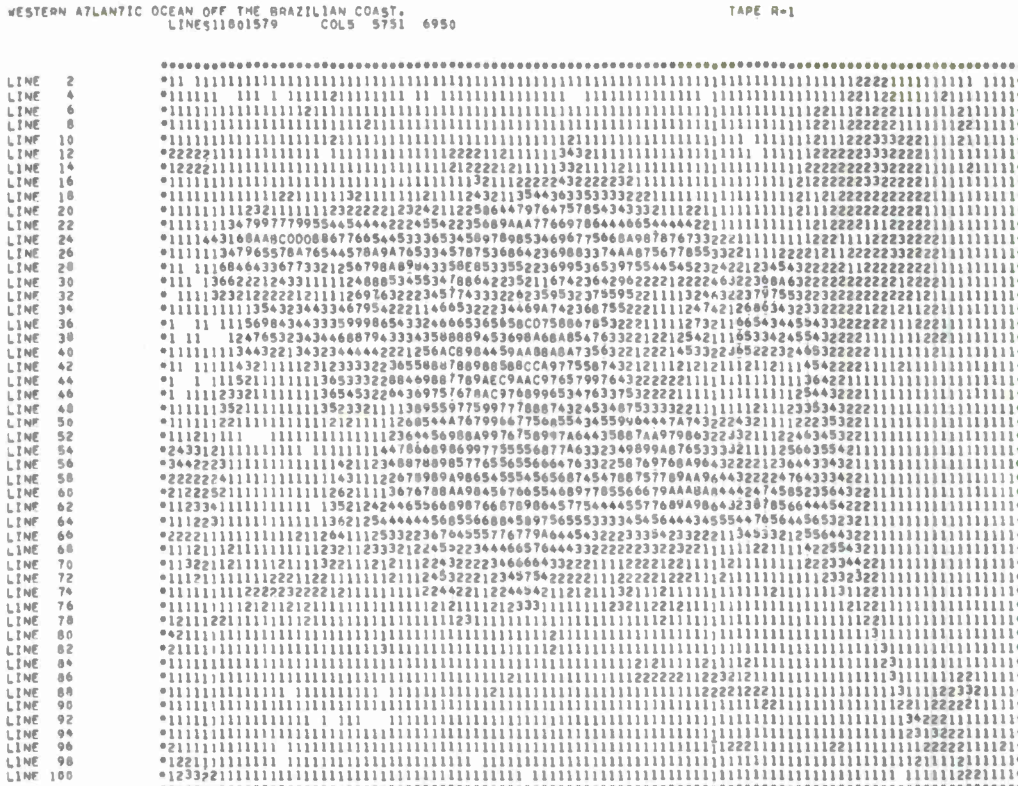
B. Clouds off the African Coast

Visual material analogous to that shown in Section A above is available for the present region; however, to conserve the reader's time, only a few selected illustrations will be used. Figures 22 and 23 show CRT plots of the digital data for the area. For tape R-1 the 300 brightest points and the centers found by ISODATA are shown in Figure 24. Using these centers as the initial guess on tape R-2, the group centers of Figure 25 are computed. Both sets of brightness centers, and the 15 matching pairs, are shown in Figure 26. In our opinion, they have sufficient uniformity to be meteorologically reasonable. The average displacement components for the region, printed in the lower left corner, are computed without using the motions near the edge, which may be unreliable, as discussed earlier.

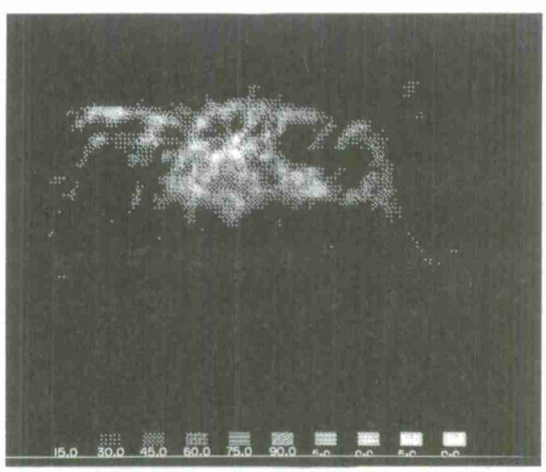
C. A Portion of the Intertropical Convergence Zone

The examples shown above indicate that reasonable looking vectors are obtained for some typical cloud systems having motions that are relatively uniform. However, many of the most significant atmospheric phenomena contain a variety of clouds whose motions vary both in the vertical and horizontal. One such phenomenon is the ITCZ. We have made some preliminary experiments with ITCZ data, but considerable additional logic will be needed to treat it adequately.

A printout of digital brightness data and a CRT picture for tape R-1 are shown in Figure 27, and Figure 28 shows similar information for tape R-2. The divisions between grey levels have been set differently than in previous CRT pictures, to give greater emphasis to the brightest elements. The brightness values cover a wide range, from approximately 200 (denoted by the letter J in the digital printout), down to the ocean background (1's and 2's). Brightness centers found by ISODATA for the 300 brightest points are portrayed in Figures 29 and 30. The matched pairs of Figure 31 indicate a rather uniform westward motion, which seems reasonable. To track other elements of intermediate brightness, 300 points (having a brightness range of 61 to 75) were selected on the two tapes. These points and the brightness centers found by ISODATA are shown in Figures 32 and 33. By reference to Figures 27 and 28, it can be seen that most of these points lie along the edge of the brightest region. The matched pairs of centers are shown in Figure 34. The results are quite erratic, and therefore suspicious. Other similar cases using a range of intermediate brightness also gave erratic cloud motions. This indicates tentatively that the "slicing" of brightness for cases of this type only gives satisfactory results for the brightest elements, whereas the points of intermediate brightness mainly represent cloud edges which should not be tracked. Further study of such cases is required. Some possible methods for dealing with them are discussed in Section VIII. Looking toward the SMS satellites, it is probable that the availability of IR data will aid in interpreting such cases.



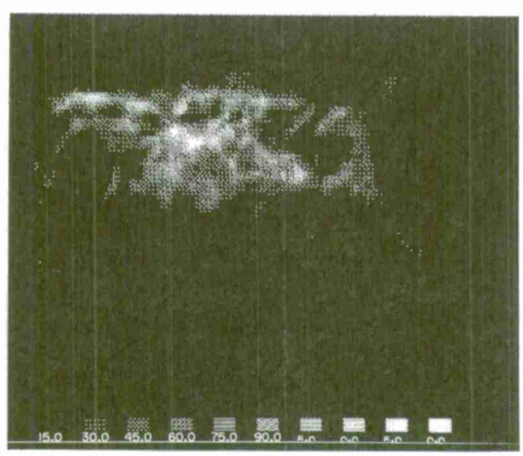
(a) EACH DIGIT REPRESENTS THE BRIGHTNESS IN A 5 BY 5 MILE ELEMENT. The digit 1 represents brightness of 10–19, 2 represents 20–29, etc.



(b) REPRESENTATIONS OF THE SAME BRIGHTNESS DATA ON A COMPUTER-CONTROLLED CATHODE-RAY-TUBE DISPLAY USING A 10-LEVEL GRAY SCALE

FIGURE 11 REPRESENTATION OF BRIGHTNESS VALUES FOR A 250 BY 500 MILE REGION IN THE ATLANTIC OFF THE BRAZILIAN COAST AT 1602 GMT, 24 JUNE 1970 (TAPE R-1)

(a) **EACH DIGIT REPRESENTS THE BRIGHTNESS IN A 5 BY 5 MILE ELEMENT.** The digit 1 represents brightness of 10–19, 2 represents 20–29, etc.



(b) **REPRESENTATIONS OF THE SAME BRIGHTNESS DATA ON A COMPUTER-CONTROLLED CATHODE-RAY-TUBE DISPLAY USING A 10-LEVEL GRAY SCALE**

FIGURE 12 REPRESENTATION OF BRIGHTNESS VALUES FOR A 250 BY 500 MILE REGION IN THE ATLANTIC OFF THE BRAZILIAN COAST AT 1628 GMT, 24 JUNE 1970 (TAPE R-2)

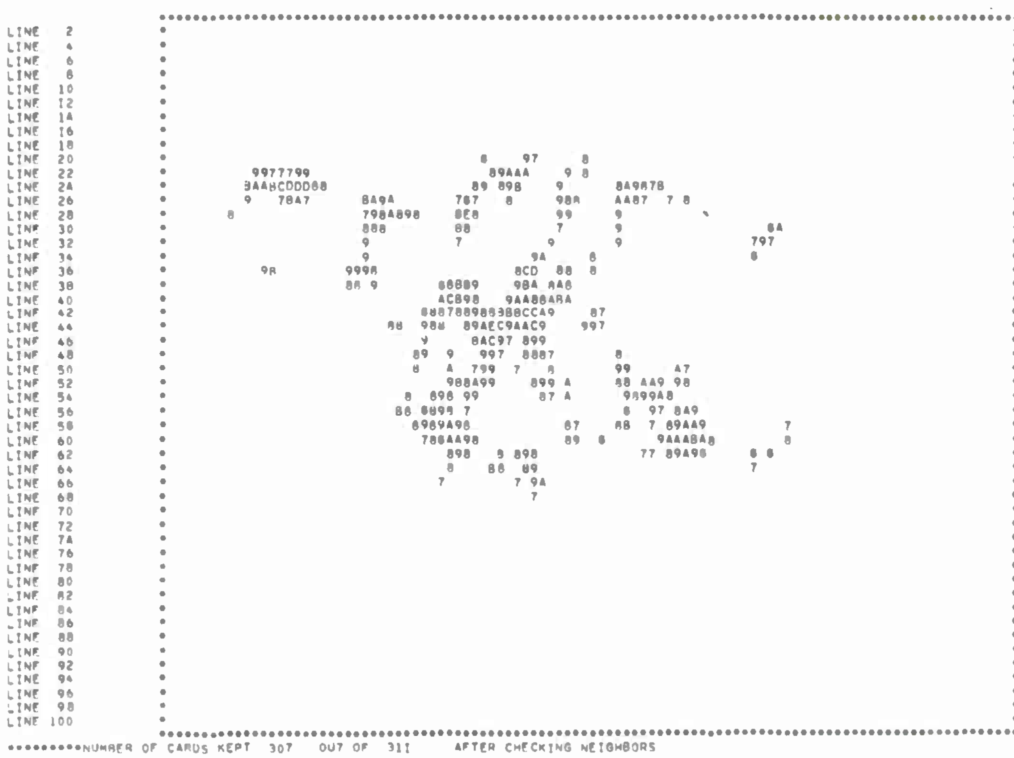


FIGURE 13 COMPUTER PRINTOUT OF THE BRIGHTEST 300 POINTS OF FIGURE 11 (TAPE R-1)

FIGURE 14 COMPUTER PRINTOUT OF THE BRIGHTEST 300 POINTS OF FIGURE 12 (TAPE R-2)

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WESTERN ATLANTIC OCEAN OFF THE BRAZILIAN COAST.
TAPE R-1            LINES 1180 TO 1579      COL 5751 TO 6950      GREY 77 TO 500
 12 INITIAL CC-S GENERATED USING A SPHERE FACTOR OF     20.0000
```

ITER	CLUSTERS	TOTAL SQUARED ERROR PER CENT	RANDOM	THETAN	THETAC	NCLST	LUMP SPLIT	PATTERNS	DISCARDS
1	12	5.598	19.079	0	10.0	2	SPLIT	307	0
2	14	3.975	17.215	0	10.0	2	SPLIT	307	0
3	16	3.346	15.749	0	10.0	2	SPLIT	307	0
4	16	3.318	15.749	0	10.0	2	SPLIT	307	0

CLUST	PATTERNS	RMS DIST	CLUSTER CENTER X	Y	GREY	STANDARD DEVIATIONS X	Y	GREY	BRIGHTNESS SKEW	KURTOSIS
1	33	5.66	239.82	45.45	98.61	12.22	3.49	16.18	1.60	2.38
2	11	3.85	214.55	27.45	97.36	5.98	2.43	20.00	2.06	2.76
3	10	3.82	286.60	25.20	88.10	6.81	2.99	6.19	-.29	.83
4	24	6.48	83.00	24.83	99.96	14.87	3.65	18.35	1.67	2.50
5	23	5.99	148.78	31.04	93.00	12.04	4.29	10.61	1.10	1.57
6	14	4.69	333.57	26.00	88.93	11.67	2.39	9.55	.64	1.15
7	6	2.78	426.00	31.67	88.00	6.63	1.37	8.83	.70	1.17
8	30	6.48	198.40	42.73	92.93	15.84	3.48	12.46	1.35	1.77
9	14	5.08	277.86	53.71	87.57	9.52	3.84	8.86	.79	1.14
10	33	5.58	363.82	57.58	93.18	12.22	3.64	10.03	-.60	1.30
11	4	4.61	430.00	61.00	82.00	12.00	2.24	4.58	.40	.59
12	36	5.88	199.17	57.39	88.22	14.03	3.46	7.91	.83	1.16
13	12	4.25	253.00	64.17	86.83	11.09	1.91	7.78	.78	1.06
14	16	5.98	325.75	51.25	89.12	11.00	4.63	8.40	.93	1.27
15	29	6.27	273.59	38.83	101.45	14.86	3.46	14.92	1.31	2.09
16	12	3.92	245.00	22.33	90.67	10.05	1.80	8.80	.25	1.06

```
SQUARED ERROR =          9643.38
PER CENT ERROR =         3.31813              290627.
THEORETICAL ERROR  =     15.7490

RMS AVG DIST. OF PATTERNS FROM THEIR CENTERS =          5.605


AVG. DIST. FROM EACH CLUSTER CENTER TO THE OTHER CLUSTER CENTERS
           31.7455    37.0226    35.4767    69.7765    49.3374    40.7533    60.6586    36.9460    33.1876    45.8666
           63.6985    40.8319    38.7693    36.9874    30.8717    36.6873

AVG. DIST. BETWEEN CLUSTER CENTERS =        43.039
```

FIGURE 15   COMPUTER PRINTOUT OF INFORMATION ABOUT GROUPS FROM THE ISODATA PROGRAM FOR THE DATA SHOWN IN FIGURE 13

WESTERN ATLANTIC OCEAN OFF THE BRAZILIAN COAST.
TAPE R-2 LINES 1168 TO 1567 COL 5749 TO 6948 GREY 77 TO 500

ITER	CLUSTERS	TOTAL SQUARED ERROR PER CENT	TOTAL SQUARED ERROR RANDOM	THETAN	THETAC	NCLST	LUMP SPLIT	PATTERNS	DISCARDS
1	16	3.487	15.749	0	10.0	2	SPLIT	304	0
2	17	3.132	15.125	0	10.0	2	SPLIT	304	0
3	17	3.132	15.125	0	10.0	2	SPLIT	304	0

CLUST	PATTERNS	RMS DIST	CLUSTER CENTER X	Y	GREY	STANDARD DEVIATIONS X	Y	GREY	BRIGHTNESS SKEW	KURTOSIS
1	36	5.83	237.00	42.78	102.17	12.45	3.66	16.56	1.48	2.35
2	12	3.82	204.50	26.83	103.25	6.22	2.51	18.02	1.67	2.51
3	13	3.80	275.38	25.08	88.23	8.54	2.43	6.10	.42	.79
4	14	5.85	55.00	26.29	93.57	10.82	4.46	10.33	.90	1.49
5	30	6.61	138.80	29.80	91.57	14.18	4.42	12.22	1.17	1.62
6	16	3.94	314.12	26.00	90.62	8.14	2.65	9.61	.81	1.25
7	6	4.18	416.00	32.00	87.17	10.20	2.31	7.03	-.53	.87
8	43	6.52	193.07	42.79	98.12	16.08	3.37	14.06	1.44	2.09
9	11	4.98	278.91	55.45	83.82	9.51	3.73	8.56	1.05	1.28
10	20	4.93	361.00	57.70	94.45	9.77	3.59	8.19	.34	1.09
11	4	2.22	430.00	59.50	81.75	4.24	1.66	3.56	.23	.47
12	25	5.07	191.44	55.68	85.00	11.42	3.28	5.75	.47	.73
13	2	1.02	250.00	67.00	79.00	0.00	1.00	2.00	0.00	.22
14	21	5.44	324.00	51.81	84.86	11.61	3.75	6.37	.71	.97
15	27	6.39	275.11	38.44	93.15	15.67	3.54	8.94	.82	1.30
16	8	3.72	236.50	22.00	92.37	10.28	1.00	9.47	-.59	1.27
17	16	4.21	89.87	23.87	100.44	10.55	1.49	16.03	1.33	2.19

SQUARED ERROR = 9101.65
PER CENT ERROR = 3.13173 290627.
THEORETICAL ERROR = 15.1252

RMS AVG DIST. OF PATTERNS FROM THEIR CENTERS = 5.472

AVG. DIST. FROM EACH CLUSTER CENTER TO THE OTHER CLUSTER CENTERS
33.5480 38.4350 37.3577 72.3336 49.0626 41.4614 63.1044 37.7777 37.2978 50.2162
68.7661 41.6643 43.2077 41.1906 33.8889 38.2239 62.5857

AVG. DIST. BETWEEN CLUSTER CENTERS = 46.478

FIGURE 16 COMPUTER PRINTOUT FROM ISODATA FOR FIGURE 14

CONVERGED AFTER 4 ITERATIONS

FIGURE 17 COMPUTER PRINTOUT OF THE POINTS OF FIGURE 13 ALONG WITH BRIGHTNESS CENTERS. The dots represent cloud elements and the C's represent brightness centers selected by ISODATA. Points belong to groups represented by the nearest center. (The C's may overlie data points.)

CONVERGED AFTER 3 ITERATIONS

FIGURE 18 CLOUD ELEMENTS FROM FIGURE 14 AND BRIGHTNESS CENTERS

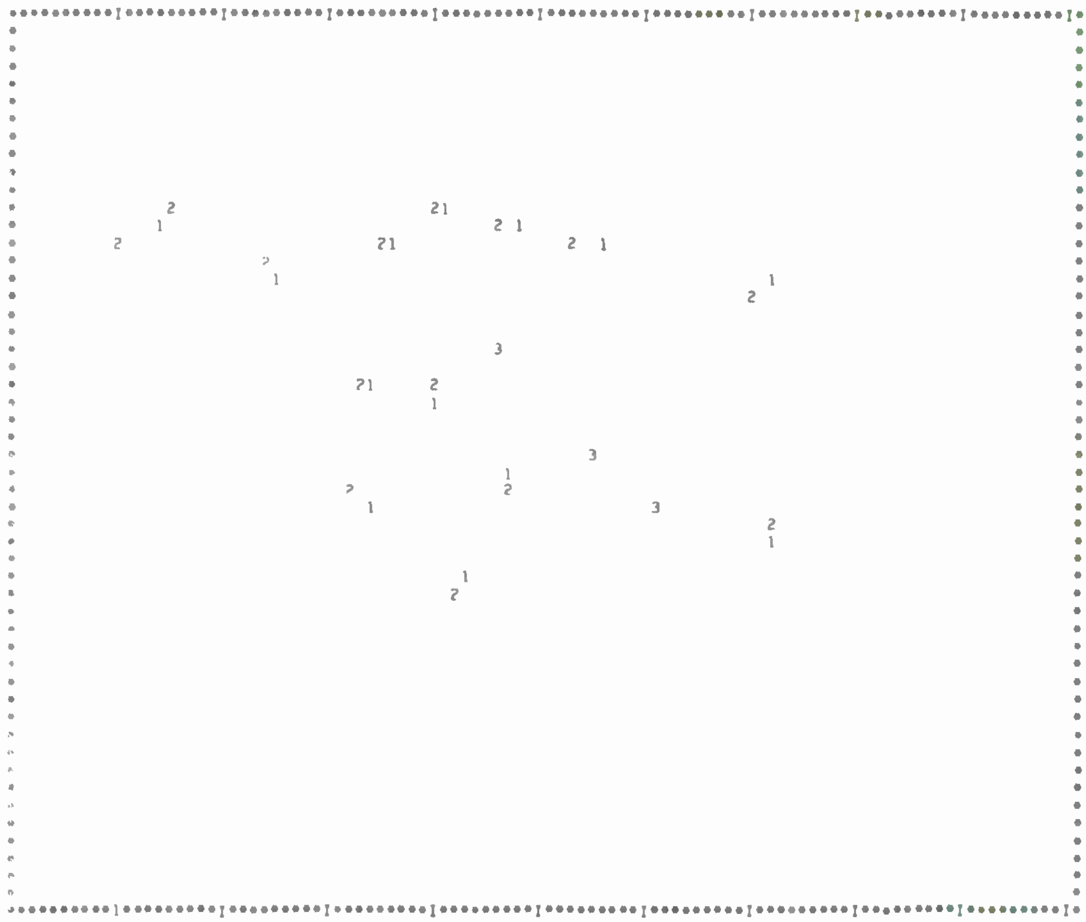


FIGURE 19 BRIGHTNESS CENTERS ON TWO CONSECUTIVE PICTURES. The brightness centers from Figure 17 are represented by 1's, and those from Figure 18 are represented by 2's, while 3's represent superposed 1's and 2's.

BEGIN ITERATION 3

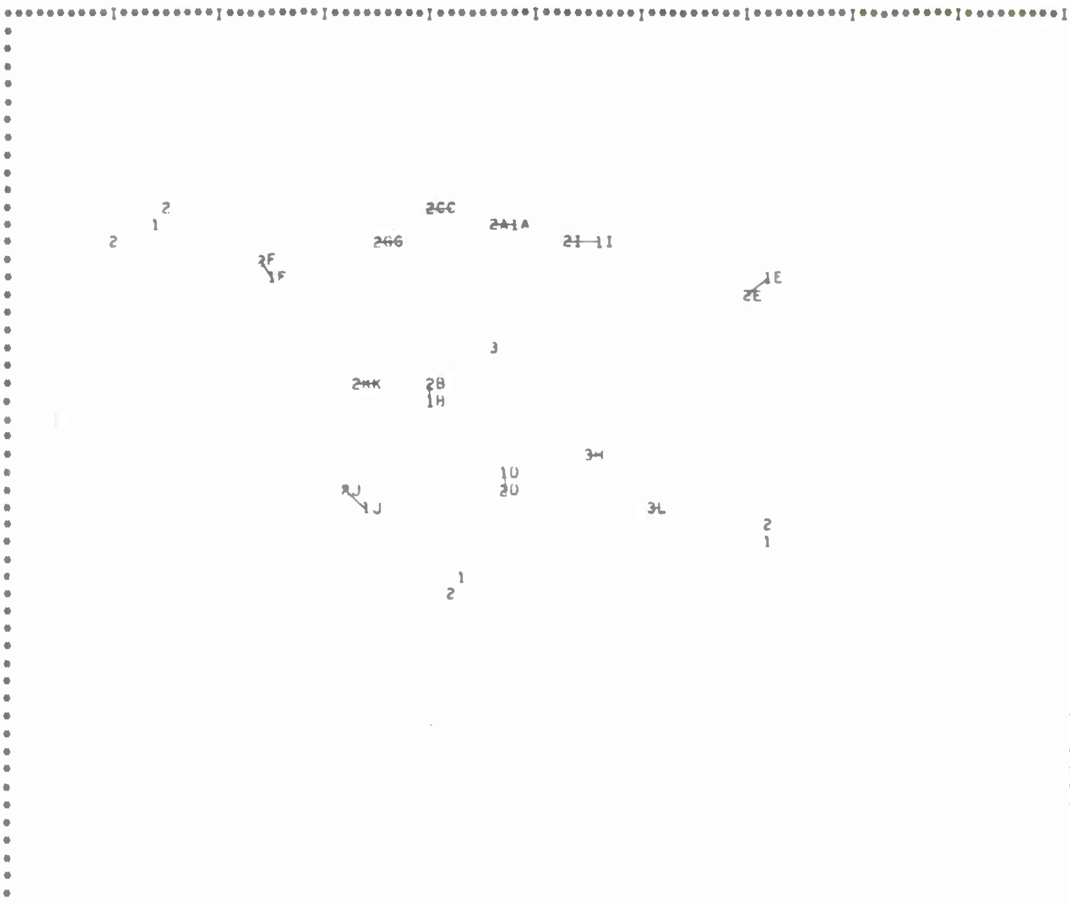
FITTING FACTOR

4.8	28.2	34.8	64.8	36.5	38.1	68.5	16.4	31.5	47.3	76.9	28.2	49.7	38.1	21.0	33.0	54.0
28.8	6.9	33.0	54.2	33.6	40.0	73.7	33.1	43.7	63.2	86.7	41.5	56.4	53.7	36.8	21.9	41.2
38.0	35.0	$\boxed{4.6}$	76.0	52.4	14.3	46.4	46.4	31.5	44.3	61.9	45.3	47.6	33.3	25.0	17.7	67.1
57.3	46.1	71.3	19.1	25.3	81.8	116.9	45.0	78.7	102.2	128.9	55.6	85.4	90.3	69.6	58.0	11.5
37.2	29.4	46.6	30.5	6.7	58.1	93.0	26.1	53.8	77.9	103.8	31.9	61.8	65.0	45.4	35.7	23.2
41.8	46.3	18.8	91.1	64.5	7.5	31.9	53.4	34.7	35.1	52.3	55.5	56.5	27.7	25.1	31.5	80.7
69.5	75.3	49.5	122.4	96.8	37.4	6.7	83.3	53.6	36.7	30.7	82.3	69.5	41.8	54.3	62.3	112.2
19.8	29.5	38.7	50.7	22.0	46.9	79.2	9.6	38.1	60.0	88.0	20.3	52.0	47.6	28.6	32.7	42.2
29.5	41.2	28.8	77.4	52.5	31.2	53.6	38.1	5.8	31.4	56.1	28.9	30.0	19.4	21.3	34.7	69.6
44.9	64.2	45.8	106.4	78.1	37.2	39.4	57.9	32.8	10.3	39.5	56.7	53.1	18.0	34.0	57.2	96.9
74.9	87.0	62.5	129.1	103.6	53.7	29.8	87.0	50.0	30.3	12.6	80.1	61.6	38.6	59.9	74.8	120.8
28.4	43.2	46.2	58.1	33.8	53.7	82.1	20.5	35.1	57.8	85.0	9.5	43.6	45.5	34.1	44.2	53.1
34.5	46.4	40.2	74.6	52.5	44.7	65.2	38.6	14.5	40.1	63.6	23.2	25.4	29.8	31.3	42.7	68.5
36.8	50.6	30.5	91.7	65.2	25.7	39.1	48.8	16.2	16.9	43.1	44.0	40.1	7.2	22.8	41.4	83.0
12.7	31.1	28.5	73.8	45.0	28.2	57.4	26.8	31.5	40.2	69.7	38.1	54.1	32.4	13.0	30.0	62.2
32.2	23.7	13.8	61.7	38.1	26.0	60.5	36.4	36.9	54.9	74.2	39.6	52.2	42.7	25.6	5.1	52.0

CRITICAL VALUE = 10.0 NUMBER OF PAIRS MATCHED = 12

	CENTER1	CENT2	U	V	X	Y	Z	BR.CHANGE	NO.PTS	DIFF.PTS	FIT	DIFF.SGX	DIFF.SGY	DIFF.SGZ
A	3	3	-3.7	.1	281.0	25.1	88.2	.1	11.5	3.0	3.2	1.7	-.6	-.1
B	1	1	-.9	2.7	238.4	44.1	100.4	3.6	34.5	3.0	4.2	.2	.2	.4
C	16	16	-2.8	.3	240.7	22.2	91.5	1.7	10.0	-4.0	3.9	.2	-.8	.7
D	9	9	.3	-1.7	278.4	54.6	85.7	-3.8	12.5	-3.0	6.2	-.0	-.1	-.3
E	7	7	-3.3	-.3	421.0	31.8	87.6	-.8	6.0	0.0	5.4	3.6	.9	-1.8
F	5	5	-3.3	1.2	143.8	30.4	92.3	-1.4	26.5	7.0	5.4	2.1	.1	1.6
G	2	2	-3.4	.6	209.5	27.1	100.3	5.9	11.5	1.0	5.6	.2	.1	-2.0
H	14	14	-.6	-.6	324.9	51.5	87.0	-4.3	18.5	5.0	6.8	.6	-.9	-2.0
I	6	6	-6.5	0.0	323.8	26.0	89.8	1.7	15.0	2.0	6.0	-3.5	.3	.1
J	12	12	-2.6	1.7	195.3	56.5	86.6	-3.2	30.5	-11.0	8.4	-2.6	-.2	-2.2
K	8	8	-1.8	-.1	195.7	42.8	95.5	5.2	36.5	13.0	8.6	.2	-.1	1.6
L	10	10	-.9	-.1	362.4	57.6	93.8	1.3	26.5	-13.0	9.7	-2.5	-.0	-1.8
M	4	17	2.3	1.0	86.4	24.4	100.2	.5	20.0	-8.0	12.4	-4.3	-2.2	-2.3
N	11	11	0.0	1.5	430.0	60.2	81.9	-.3	4.0	0.0	12.5	-7.8	-.6	-1.0
O	15	15	.5	.4	274.4	38.6	97.3	-8.3	28.0	-2.0	13.3	.8	.1	-6.0
P	13	13	-1.0	-2.8	251.5	65.6	82.9	-7.8	7.0	-10.0	25.2	-11.1	-.9	-5.8

FIGURE 20 COMPUTER PRINTOUT OF INFORMATION FROM THE MOTION PROGRAM. The upper table shows the "FIT" between all pairs of centers. The lower table shows matched pairs, motion components (u and v), location, etc.



AVERAGE U	AVERAGE V	NO.VECTORS
-2.46	.32	12.00

FIGURE 21 THE BRIGHTNESS CENTERS MATCHED IN PAIRS BY THE MOTION PROGRAM. The pairs are denoted by alphabetical letters. Brightness center motions are from 1's to 2's.

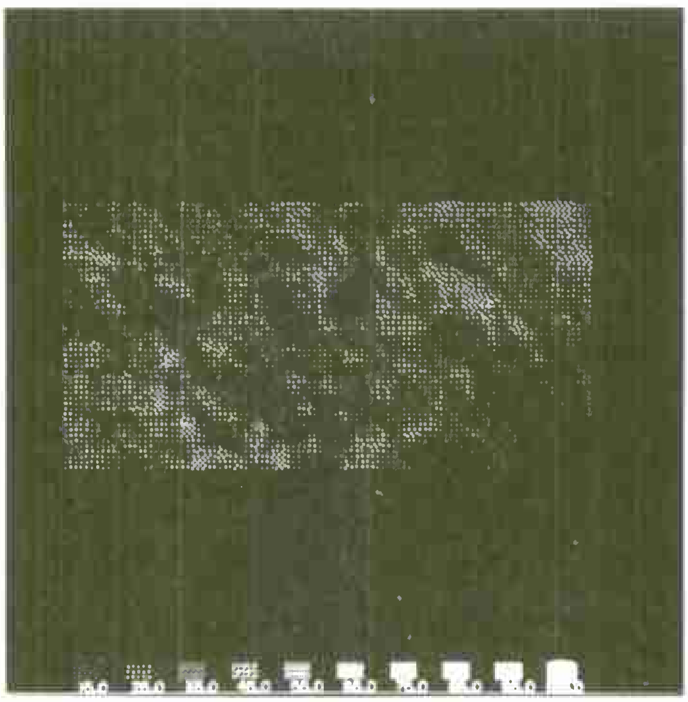


FIGURE 22 A CRT DISPLAY OF BRIGHTNESS DATA FOR A PORTION OF THE EASTERN ATLANTIC (TAPE R-1)

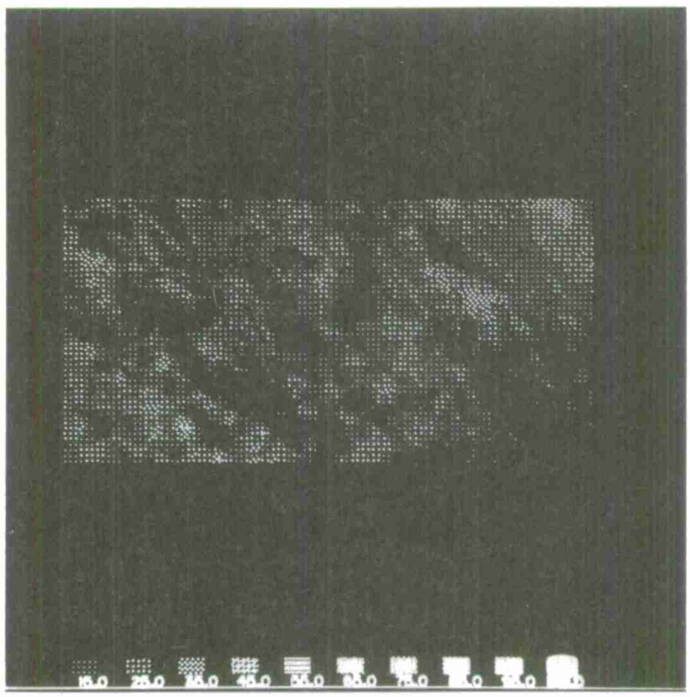


FIGURE 23 A CRT DISPLAY OF BRIGHTNESS DATA FOR A PORTION OF THE EASTERN ATLANTIC (TAPE R-2)

CONVERGED AFTER 3 ITERATIONS

FIGURE 24 COMPUTER PRINTOUT OF THE 300 BRIGHTEST ELEMENTS FROM FIGURE 22 (TAPE R-1) ALONG WHICH BRIGHTNESS CENTERS FOUND BY ISODATA

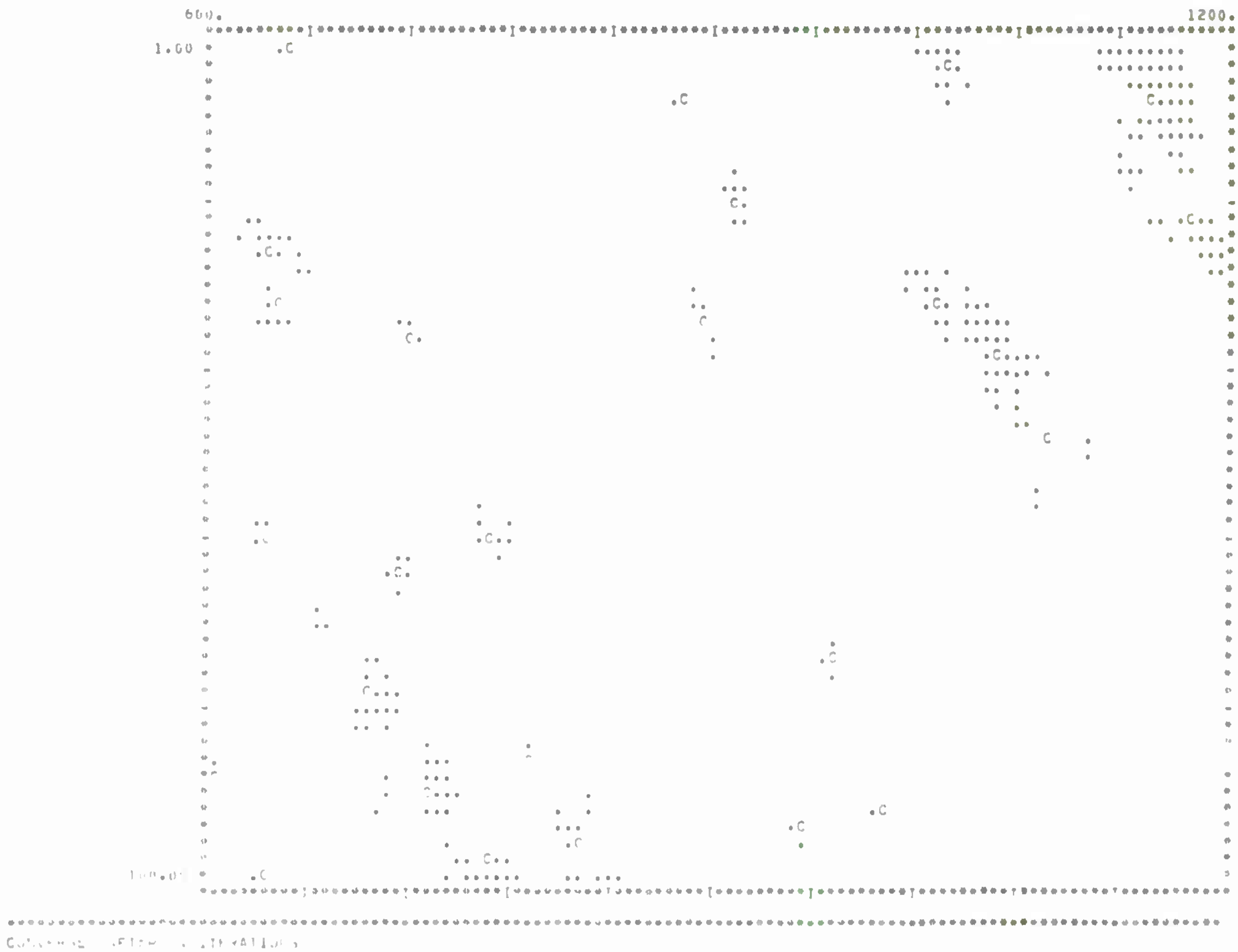
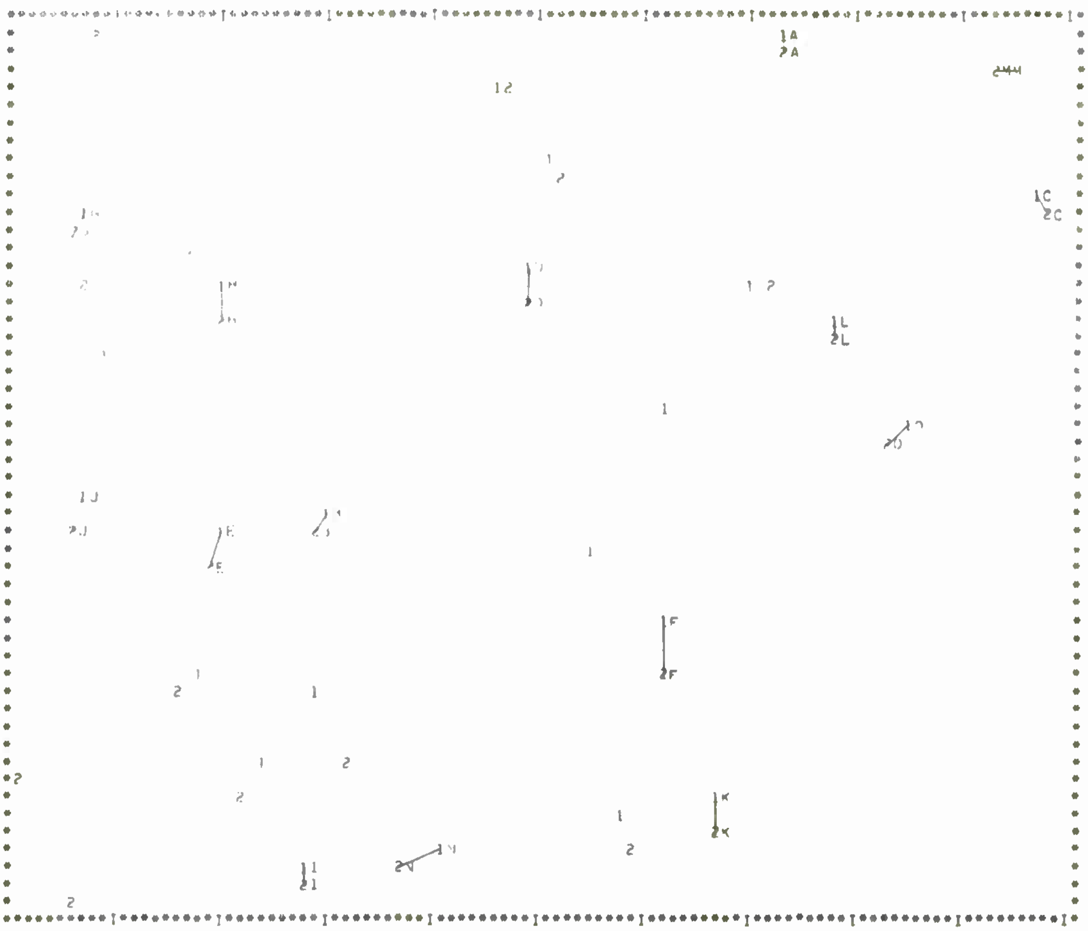


FIGURE 25 COMPUTER PRINTOUT OF THE 300 BRIGHTEST ELEMENTS FROM FIGURE 23 (TAPE R-2) ALONG WITH BRIGHTNESS CENTERS FOUND BY ISODATA



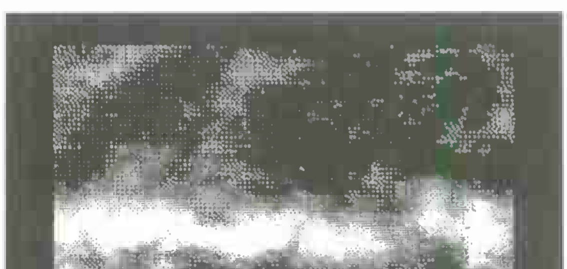
AVERAGE U	AVERAGE V	NO.VECTORS
-1.37	-3.13	9.00

FIGURE 26 THE BRIGHTNESS CENTERS MATCHED IN PAIRS BY THE MOTION PROGRAM. Cloud motions are from 1's to 2's.

```
NAGLE/RUGGLES AREA IN THE ATLANTIC OCEAN.                                    TAPE R-1
                    LINES   800  1199      COLS  4100  5299

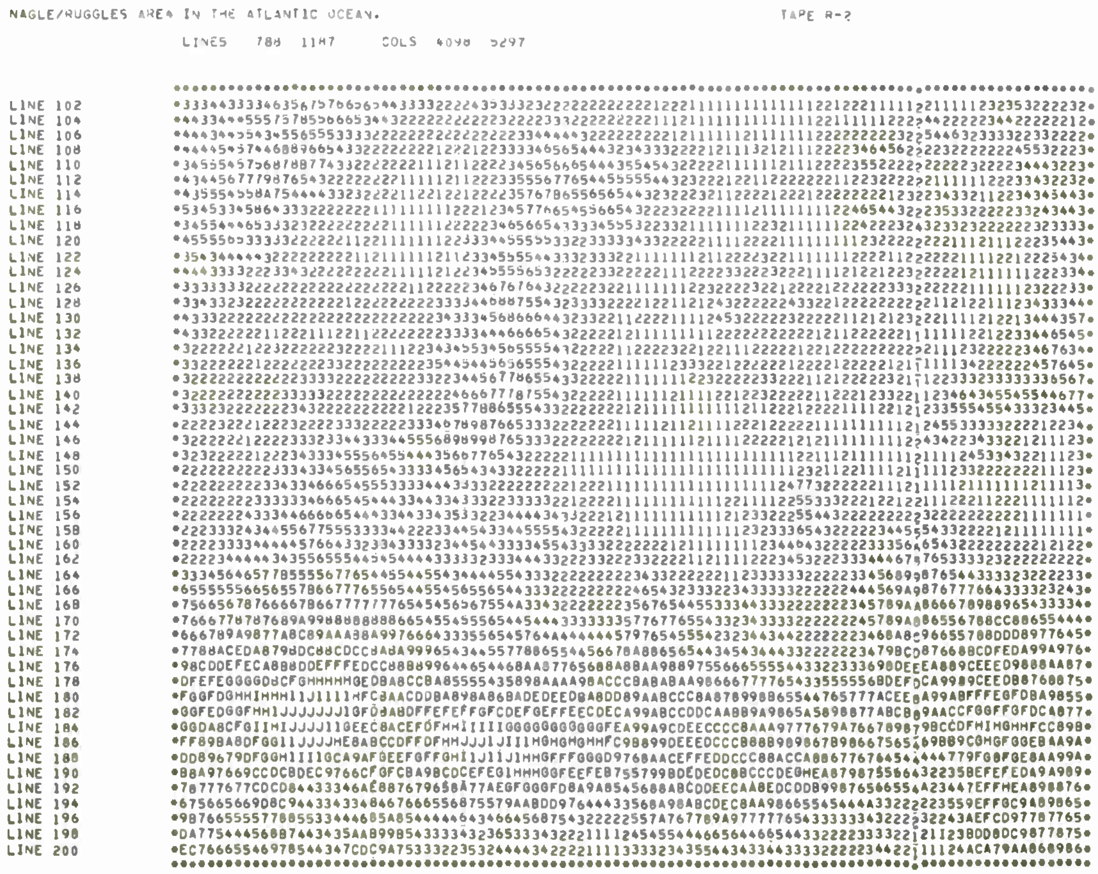
                    ********************************************************************************************************************
LINE 102            *34333232244565507555765554333322233233222222222222111212322111121122211223222222221322111122344322222*
LINE 104            *33343232343345768667654333332222222222224443322222223222221211112112121122222222333237455223334332322*
LINE 106            *43444323343236757676444332332222222232223445444322222222222221111113222111222225655732222322222454443 33*
LINE 108            *44433334333456656554333222222222222223334456554443335433322222111111222212222355332222222222223443332*
LINE 110            *44334446555578766533332222222222222223445665544434455553323221221222322112212332212221222221123333 22*
LINE 112            *44445557557879875433222222211222222223345677555445544432322222222222222211132222122212232221222323443*
LINE 114            *44556778768867543332222222222222222223457777667666543322222221111122222111113447432222155322222222333*
LINE 116            *44456566798744544322222222122222222234456655555454322222222111122222111122355223335322233222222334*
LINE 118            *54474335785334322232222222212222222333355544433333333343223221112221211112332433322322222222222222333*
LINE 120            *55554444445333222222222222221122222333454454332222222212221222122222222211122222221123222211222222223443*
LINE 122            *45554664332323322222222222221111223334443441223222222221122112122222222111112122111111122221222222223564*
LINE 124            *44434445332333222222222222221121223344444222222222221111122222222222222211223222231422222222211222333*
LINE 126            *44544433322222222222222222223222223345554432222222111112112222322222243322222223222122222222321122233 3*
LINE 128            *34333333222222222222222222342223355555432222222222222221222432222223322222212112332111222221233334*
LINE 130            *43443343222222222222221222223433223444444322222211122222221112222222222222222222223322212124222223455 4*
LINE 132            *55333343222333222222222122212343322223443332222211111123322222221112222122224222222222111232222234577 5*
LINE 134            *43334332222222222222222212222232222223342232222112111121233332221222222222222232222211112432222246885*
LINE 136            *44333322222222222222222222232222223443222321221211111111112232222222221122223333221112323222123 45786*
LINE 138            *44443332323222222222222222223322234454322232222221211111121112223332212122112222211113444222234445 77*
LINE 140            *44332222222222222222223322222222123433433323332212222122111111122233233222222121222222224433334344 5556*
LINE 142            *4432222222222222222223322222222222334333333222222221111222122211223321222212222211112234443333333334 5*
LINE 144            *34322222222222322222222222222222223455433222222222211112112111211112222221122222111122354533333222222 23*
LINE 146            *53332322222223333444432222332222235666433333322222111111111111111211212222112212111222223234322332222 2*
LINE 148            *3322222222222336565444545554332233533544532222212211121111111111111111211112222111111222122365323542 2222*
LINE 150            *22222222222333445445655543332223332223222222111111111111111111111111112222211112111222222123222111*
LINE 152            *22222222222333434545565433333343343333322222121221111211111111111111121222222122111111111111112221111*
LINE 154            *32222222222233445655545543322333445643444432222212111111111111111111243222222221111222222222222211211*
LINE 156            *22222222222344457765554433223333565543554433332222221122221111121221222663333222212222222122221111212*
LINE 158            *22222222332345676755444432322240754455544554432222221222212212223322245333322222212222222111111111112*
LINE 160            *22222322333455688765333334323344433232444544433222222222122122111322435554332232334444332222222212122 2*
LINE 162            *33322333345665577776433344333433333334553332333222322211211111111224554433333454657764432323332222222*
LINE 164            *33322245555666566665544444434454334444543333322332222322222221222222233344333455657488865434333222222 2*
LINE 166            *44333456766676665455544444444655655654433332222222222443222222222233332333333455568949975545333333 2233*
LINE 168            *66546667887887676787667666555666777655544443322232236754333332234433333323345668948897655776544333 45*
LINE 170            *9867888999989999998789A988676665777765554544343433356676654442224444333323335669A9CC96657A8DD8866566*
LINE 172            *A889994DCH89AABBA99BA4CA99887665666765666555566544577666654433222444443322344458800CA766798EFFDA9767*
LINE 174            *849A8CDDECCAAACC894CDEDCH89AA96555665677977778666899999656443344335444322233446 9CFEEC87778BEGFECA999*
LINE 176            *CCCDEDDDDDDB9ACEEEFFGFFECDDDCA8545644799 8A7A897998CCDC887965557765666544333 45698EFGGEA779CFGHGE89A8C*
LINE 178            *DFFFFFEEHHFECEGHHH111HGEDCDDDC96554445 8ABCACDDA8CDDDED8888A87667888876544556 78ADFGGHFC9AACEEFGD88888*
LINE 180            *FFGHGFDG1HHGGHJJJJJJJ1GDDCCEEEA767587688CDDFFEDCDEEECACDDDC8A87499A87655555 6999CF3HEDC8D8CFFFGGCBAAA*
LINE 182            *GGGHGECGGHHH1JJJJJJJJ1HECCDFGFDEDCAEDCDEGGFGGGFFFFECHBCDEEEDCAA8CB8A97765678 8888D0DAACCECGHGGHGFD8A*
LINE 184            *HGHGDBADFFGGH1JJJJJJGEECHCEFGHGIH11J1HHH11HH1HH11HECHDCDEFFFD8CDDCCC89977689 86689C49ACDEEGIHEHH13ECH*
LINE 186            *FFGFCA9ADEGFH111J11HDAADCDCFGFFH1111JJJ1111111111HF88DCCGGGGECCDDDDDCA887667 777559788ADC888GEHH1HECH*
LINE 188            *BADEB96790GGGFH11HEB98DGEBDFEEFGEFG11111HHHHHHHGEB9ACCDFGGGEDDDEDDDCC898766 7774545535 8A89EFEFHFECB9*
LINE 190            *788999888900D498A96556 4EGD979899AAADEH1HI1HHGFFFFD977CCDFGGFFEDDDDDEGHEA98777656454323588FFEFDECB89*
LINE 192            *8949999767 8D9864333357 8A866664467879CDEFGHGFD8A89865698CEEFEFFD8A8CC8CDCA97656764443223456EGDD899998*
LINE 194            *9876566655 7AA455434435584445334454646 9A9BDE987544454 88A88A8DEFF899AA987776555443332323466EFD8677666*
LINE 196            *8777664443477865433565596665333345578856785443432348788877 79C88778877765444443333322224 56EFCD987655*
LINE 198            *7AC97754445787564434 7ACDCA6543322234366674443323322467444544556544665555433344354521121237EDA8388667*
LINE 200            *8EEE977776786545444 56 JE8885433222223243335432322222333344444333543455454323333443522221228D887799787*
                    ********************************************************************************************************************
```

(a) DIGITAL PRINTOUT

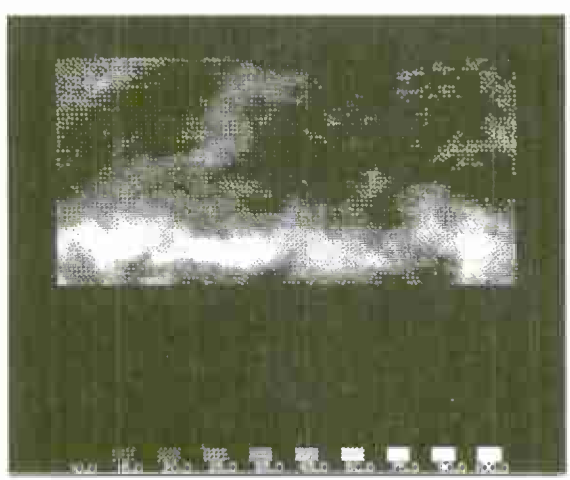


(b) CRT DISPLAY OF THE BRIGHTNESS DATA

FIGURE 27 REPRESENTATION OF BRIGHTNESS VALUES FOR A 250 BY 500 MILE PORTION OF THE ITCZ FROM TAPE R-1

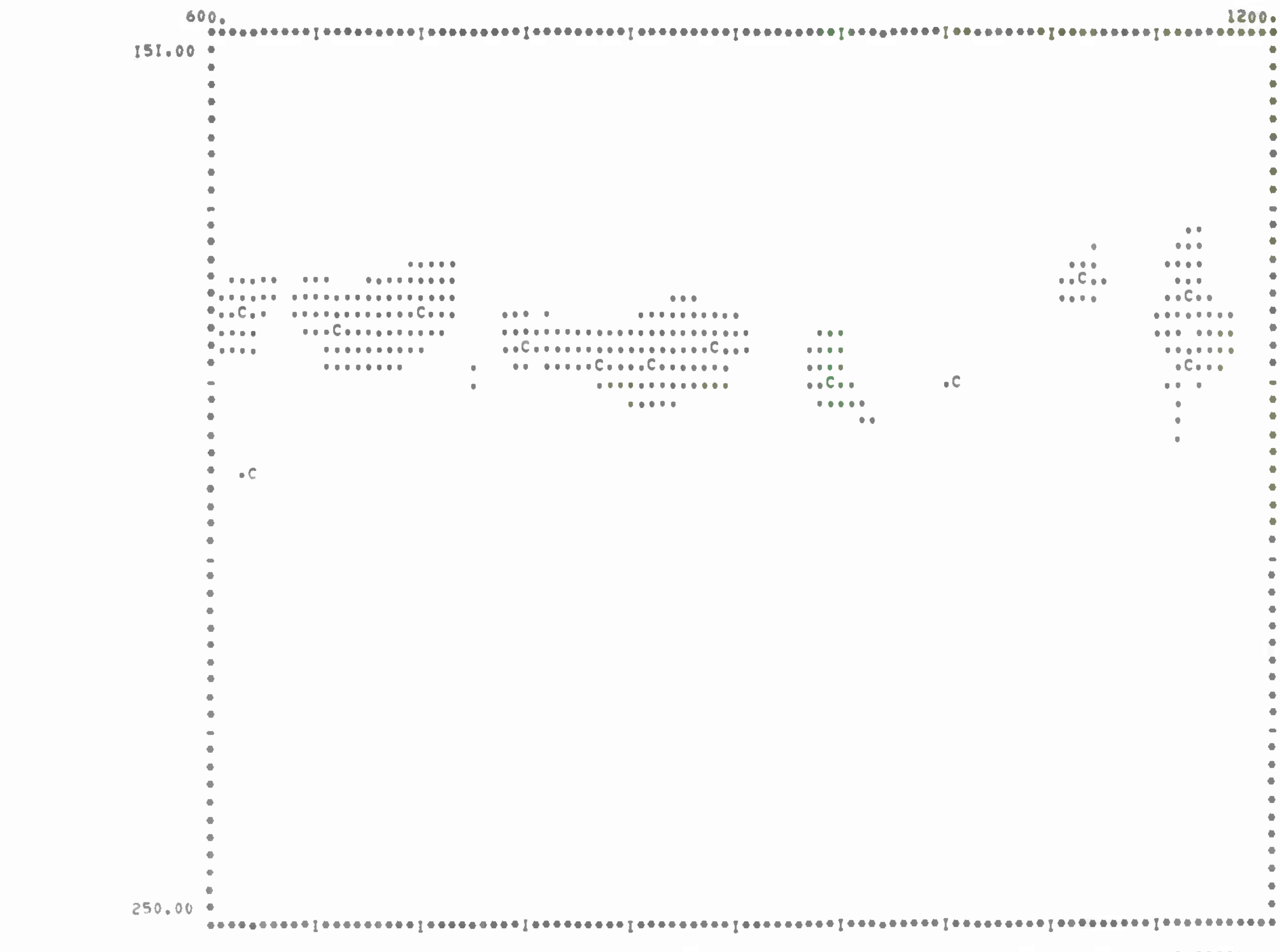


(a) DIGITAL PRINTOUT



(b) CRT DISPLAY OF THE BRIGHTNESS DATA

FIGURE 28 REPRESENTATION OF BRIGHTNESS VALUES FOR A 250 BY 500 MILE PORTION OF THE ITCZ FROM TAPE R-2



CONVERGED AFTER 3 ITERATIONS

FIGURE 29 COMPUTER PRINTOUT OF THE 300 BRIGHTEST ELEMENTS FROM FIGURE 27 (TAPE R-1) ALONG WITH BRIGHTNESS CENTERS SELECTED BY ISODATA

FIGURE 30 COMPUTER PRINTOUT OF THE 300 BRIGHTEST ELEMENTS FROM FIGURE 28 (TAPE R-2) ALONG WITH BRIGHTNESS CENTERS SELECTED BY ISODATA

AVERAGE U AVERAGE V NO.VECTORS

-2.64 -.73 9.00

FIGURE 31 THE BRIGHTNESS CENTERS MATCHED IN PAIRS BY THE MOTION PROGRAM. Cloud motions are from 1's to 2's.

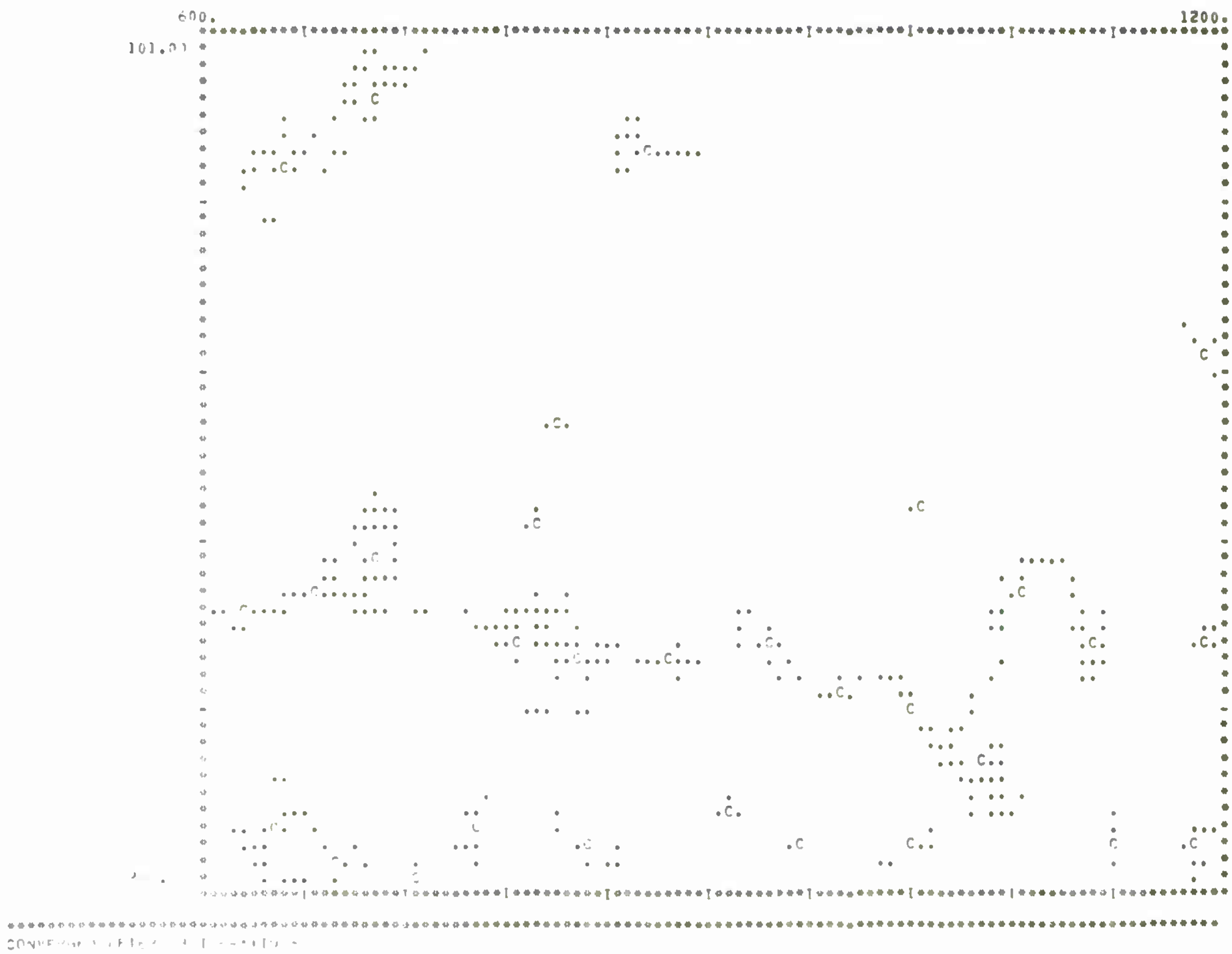
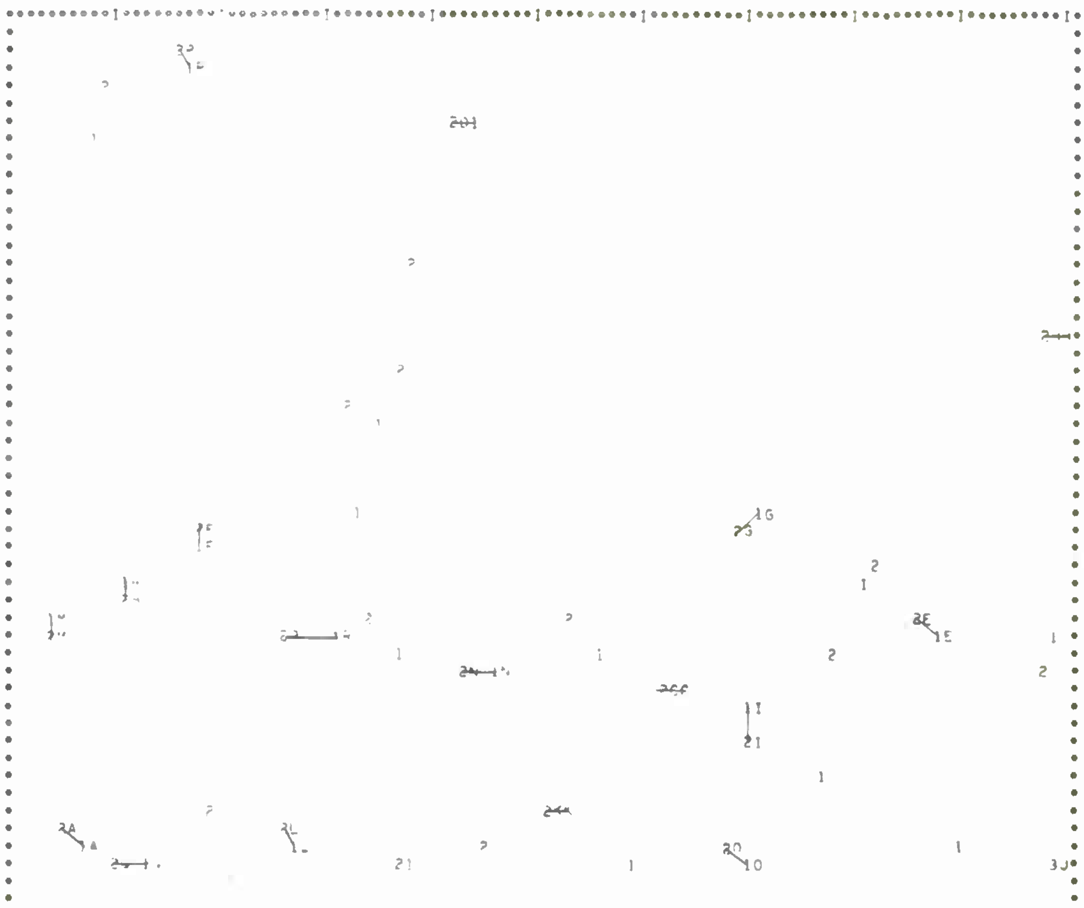


FIGURE 32 COMPUTER PRINTOUT OF 300 ELEMENTS FROM FIGURE 27 (TAPE R-1) IN THE INTERMEDIATE BRIGHTNESS RANGE 61-75 ALONG WITH BRIGHTNESS CENTERS FOUND BY ISODATA

FIGURE 33 COMPUTER PRINTOUT OF ELEMENTS IN THE BRIGHTNESS RANGE 61-75 FROM FIGURE 28 (TAPE R-2) ALONG WITH BRIGHTNESS CENTERS FOUND BY ISODATA



AVERAGE U AVERAGE V NO.VECTORS

-3.18 -.54 9.00

FIGURE 34 THE BRIGHTNESS CENTERS MATCHED IN PAIRS BY THE MOTION PROGRAM. Cloud motions are from 1's to 2's.

VI PICTURE REGISTRATION, RECTIFICATION, AND GRIDDING

The problems of registering, rectifying, and gridding ATS digital pictures are of significant importance, as mentioned in Section II. Here registration means associating equivalent locations (in tape coordinates) on two pictures. Rectification means adjusting the tape coordinates (with respect to an ideal picture) to correct for rotation, stretching, and ideally, internal deformation. Gridding is the transformation from tape coordinates to earth (geographical) coordinates. The computer programs developed in this study to perform these operations require that several landmarks be found by computer on each picture being treated. (The program MATCH, described earlier, does this.) Using the landmark locations in tape coordinates (X,Y), adjustments are made to map one picture onto another using translation, rotation, and stretching. (Further corrections to account for internal distortions of pictures, which are of relatively small magnitude, appear not to be needed at this time.) Cloud motions are determined in tape coordinates using the registered pictures. From the known latitude and longitude of the landmarks, their (X,Y) coordinates on an ideal (or nominal) picture can be computed. (The characteristics of an ideal picture are calculated assuming that the satellite remains fixed over a point on the equator at a certain distance from the earth, with its spin axis parallel to the earth's axis.) By comparing the actual coordinates of the landmarks of a particular picture to the corresponding ideal coordinates, the picture is mapped on the ideal picture, and this facilitates a transformation from picture coordinates to earth coordinates. Digital techniques for performing these operations comprise the program CORRECT, which is described below.

The procedure takes advantage of certain characteristics of ATS data. A primary characteristic is the great similarity of pictures made within a few hours (barring equipment malfunctions). This similarity allows the pictures to be used in movie loops (e.g., Fujita et al., 1968; Hubert and Whitney, 1971) or to be viewed on a TV display console (Evans and Serebreny, 1969). Greatest accuracy in visual registration is achieved by treating magnified sections of pictures in the vicinity of recognizable landmarks.

Corrections are needed because of imperfections in the satellite's orbit and attitude (User's Guide, 1969). The orbital factors vary over a period of 24 hours (approximately), and therefore the changes within an hour or so may be represented as quasi-linear. One orbital imperfection is the small inclination of the satellite's orbital plane with respect to the earth's equatorial plane. Due to this inclination, at certain hours the satellite subpoint will be north of the equator, and 12 hours later, it will be south of the equator. The latitude of the extreme excursions equals the orbital inclination. Another orbital imperfection is the eccentricity (noncircularity) or the orbit, which causes an east-west oscillation of the satellite subpoint, and minor changes in the size of the earth's photographic image. Together, these two orbital factors cause the subpoint to execute a small figure eight pattern every 24 hours crossing the equator at the nominal (or ideal) subpoint. The satellite subpoint may also undergo a gradual drift along the equator due to orbital precession.

The ATS satellites spin at approximately 100 rpm around an axis oriented approximately parallel to the earth's north-south axis. Even a slight lack of parallelism causes the earth's image to move significantly in the picture frame from one picture to another. This can be seen as follows. There are two points in the orbital path (12 hours apart) where the satellite's spin axis and the earth's axis lie in a

plane. At one of these points the northern portion of the earth's visible disk may touch or extend beyond the top of the picture frame, while at the opposite orbital point the disk lies toward the bottom of the frame. Thus in picture coordinates, the earth's disk appears to move up and down by rather large amounts. Corrections for this effect can be made rather easily by disk matching using chords, as described earlier. At two orbital points intermediate between the pair mentioned above, the satellite's spin axis departs by a maximum amount from a plane through the earth's axis and the satellite. At one of these latter points, the earth's image in the picture frame is rotated clockwise from its nominal position, and at the opposite orbital point it is rotated counterclockwise.

The basic concept we have been following for registering one picture of a daily sequence to another depends upon the use of several well-defined landmarks distributed around the picture but not lying too close to the edge of the image. On the image plane (nominally through the earth's center and perpendicular to a line joining the center and the satellite), the (X,Y) coordinates of the landmarks are found on two pictures. The MATCH program for doing this was described earlier. Because of the nature of the orbital and attitude variations discussed above, the landmarks of one picture (or image) can be made to coincide quite accurately with those on a second image by use of translation, rotation, stretching in the x direction, and stretching in the y direction. However, further corrections to images to account for internal distortions (due primarily to the figure eight motion of the subpoint) can be made by reference to the periodic nature of the orbital factors. In the pictures we have treated, such distortions are small. We have not yet begun to write computer programs to make such corrections.

Another basic aspect of the problem is the transformation from tape coordinates to latitude and longitude, i.e., gridding. As mentioned

earlier, an ideal picture would be obtained if the satellite were fixed over the equator at a certain longitude, at a known distance from the earth, with its spin axis parallel to the earth's axis. Also, the ideal photographic image of the earth's disk would be circular, with a known radius and a fixed center. Then using plane and spherical trigonometry, one can transform (X,Y) tape coordinates to (φ,λ) earth coordinates, or the reverse. These transformations are performed by the subroutines XLAT and LATX respectively, which use equations similar to those employed by L. D. Herman of the National Environmental Satellite Center.

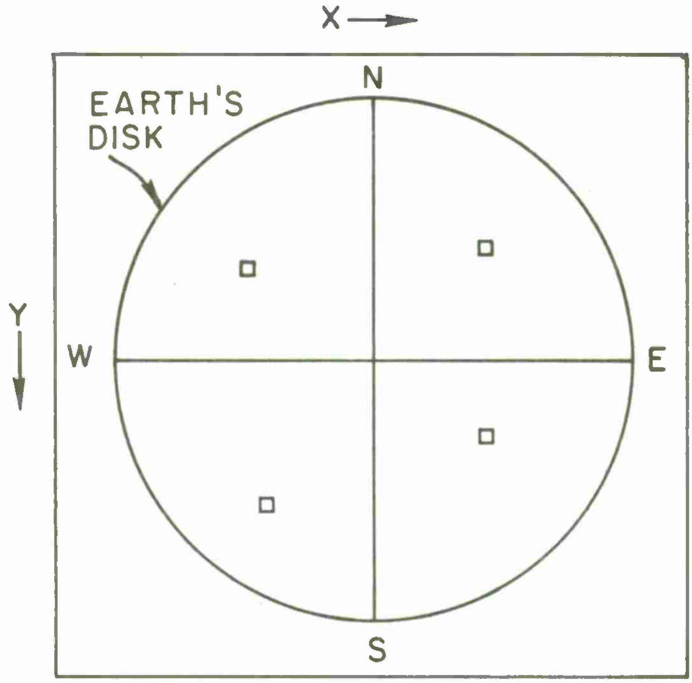
In using these techniques one can proceed as follows. The first step is to transform the tape coordinates of the landmarks so that the X and Y scales are equivalent, and the distances are measured from the nominal picture center at X = 4000, Y = 1200. That is, $X' = (X-4000)/XSCALE$ where XSCALE = 3.0, and $Y' = Y-1200$. (The factor XSCALE makes the column elements commensurate in length with row elements.) For convenience, the primes are omitted in the subsequent discussion. For several landmark templates to be used with a series of pictures, the latitude (φ) and longitude (λ) of the centers (or corners) of each template are determined as closely as possible by reference to an atlas. At present, landmarks are selected by inspection of pictures. Selecting them and determining the geographic coordinates of the templates are the only steps of the sequence that require human judgment. This operation is done using an atlas version of a landmark, which naturally has absolute or ideal gridding information on it. The geographic values of one point on the atlas are associated with the corresponding point on the template. The judgment of correspondence is the human operation required. Since an accurate atlas with a suitable scale may be used, the crucial part of this operation is in recognizing the corresponding features on the template. Using standard atlases, we believe that this can be done reliably to about the 2.5 mile resolution of the nearest single

element of the satellite image. The error enters into the location of the cloud motion vectors, but since it is the same on pictures of a sequence, it does not affect the motion vectors themselves.

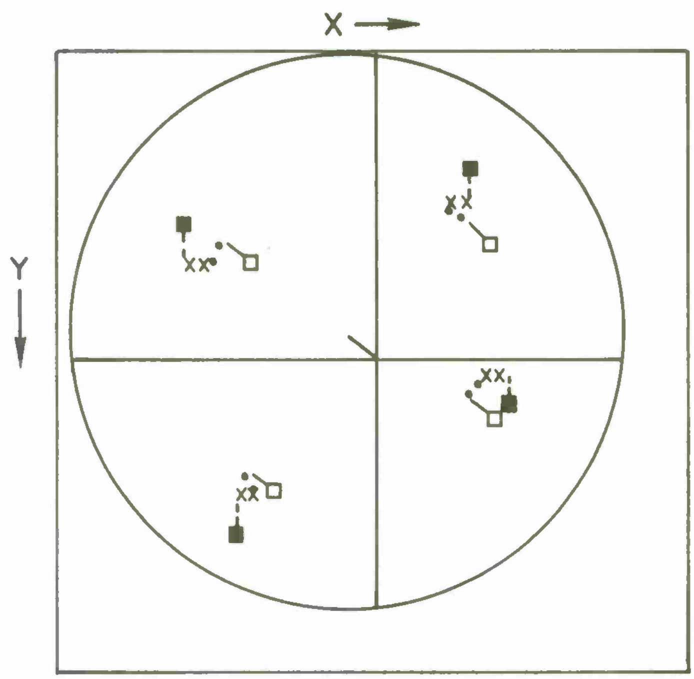
Using the subroutine LATX, the nominal locations (X_n, Y_n) in tape coordinates are computed for each landmark from its φ and λ. The subroutine REGISTER is then used to determine the corrections for translation, rotation, and stretching, to match the landmarks (X_1, Y_1) of a given picture onto the ideal picture. The translation corrections in X and Y are added to the nominal center to give the center of picture 1, which is needed in subsequent computations.

The next step is to register a second picture to the first (non-ideal) picture by comparing the landmarks, again using REGISTER. The translation corrections are applied to picture 2 to find areas that correspond to segments of picture 1 before applying ISODATA and MOTION to the pair of pictures. This gives a matching of areas that is sufficiently accurate to ensure that ISODATA and MOTION operate with intended continuity. The cloud motions from these programs are in the coordinates of picture 1, and are then corrected to account for the rotation and stretching needed to register picture 2 on picture 1. In the next step, the cloud motions and their locations in picture 1 coordinates are transformed to ideal tape coordinates (X_n, Y_n) using the corrections determined earlier to transform picture 1 to the nominal picture. Finally, using the subroutine XLAT, the transformation of cloud motions to earth coordinates is made.

The differences between one picture and another are illustrated in Figure 35(a), which depicts four landmarks at their nominal positions. Due to the factors mentioned earlier, the same landmarks appear at different positions in the image frame of a second (non-ideal) picture, and are depicted by solid squares in Figure 35(b). In greatly exaggerated



(a) IDEAL CASE



(b) LANDMARK LOCATIONS (SOLID SQUARES) AFTER TRANSLATION, ROTATION, X-STRETCHING AND Y-STRETCHING

FIGURE 35 HYPOTHETICAL LANDMARKS (SQUARES) ON A PICTURE

form, Figure 35(b) shows effects of translation as solid lines, the same for each of the landmarks. The effect of rotation, indicated by dots, is proportional to the length of the radius of each landmark from the center of the first image, and is perpendicular to the radius. The rotation shown is counterclockwise. The effect of X-stretching is proportional to the distance of the landmark from the north-south axis of Figure 35(a). This effect is illustrated for expansion by the x's in Figure 35(b). The effect of Y-stretching is proportional to the distance of the landmark from the east-west axis of Figure 35(a). This effect is indicated by the dashed line segments in Figure 35(b). Due to the orbital and attitude features mentioned earlier, X-stretching and Y-stretching may be of either the same or opposite sign. The final positions of the landmarks on the second picture are denoted by solid squares, as mentioned above.

Knowing the (X,Y) locations of the landmarks in picture 1 (denoted by open squares) and in picture 2 (denoted by solid squares), we must determine the translation, rotation, X-stretching, and Y-stretching, required to map picture 2 onto picture 1. The iterative subroutine REGISTER operates as follows.

The X correction for translation, XCT, and the Y correction, YCT, are computed as

$$XCT = \frac{1}{n} \sum_{i}^{n} (X_1 - X_2)$$

$$YCT = \frac{1}{n} \sum_{i}^{n} (Y_1 - Y_2) \quad .$$

Here the subscript 1 pertains to picture 1, 2 pertains to picture 2, and n = 4 in Figure 35. Improved values of the landmark locations on

picture 2 corrected for translation are $X_2^{(1)} = X_2 + XCT$, $Y_2^{(1)} = Y_2 + YCT$. Superscripts denote stages in the computation.

The corrections for the rotation are computed as

$$XCR = \frac{1}{n} \sum_{i}^{n} -[X_1 - X_2^{(1)}]/Y_2^{(1)}$$

$$YCR = \frac{1}{n} \sum_{i}^{n} [Y_1 - Y_2^{(1)}]/X_2^{(1)} \quad .$$

If $Y_2^{(1)}$ is rather small for a certain point, to avoid the inaccuracy of dividing by a number close to zero the point is excluded from the computations of XCR, and a similar treatment of small denominators is made in computing other corrections. For solid rotation the two corrections XCR and YCR must be the same, so that the final rotation correction is $CR = 1/2\ (XCR + YCR)$. Improved values of landmark locations are $X_2^{(2)} = X_2^{(1)} - CR \cdot Y_2^{(1)}$ and $Y_2^{(2)} = Y_2^{(1)} + CR \cdot X_2^{(1)}$.

The corrections for X-stretching and Y-stretching are computed as

$$XCS = \frac{1}{n} \sum_{i}^{n} [X_1 - X_2^{(2)}]/X_2^{(2)}$$

$$YCS = \frac{1}{n} \sum_{i}^{n} [Y_1 - Y_2^{(2)}]/Y_2^{(2)} \quad .$$

As mentioned earlier, XCS and YCS are generally not equal. Improved values of the locations of landmarks on picture 2 (with respect to picture 1) are

$$X_2^{(3)} = X_2^{(2)} + XCS \cdot X_2^{(2)}$$

$$Y_2^{(3)} = Y_2^{(2)} + YCS \cdot Y_2^{(2)} \quad .$$

The computational cycle is repeated several times giving improved values of the various corrections. It is terminated when the estimates cease improving, or when the number of iterations reaches a preset limit. In numerous test cases using data formulated to evaluate the technique, 10 iterations or less have given acceptable convergence.

The total corrections to register any point of picture 2 onto picture 1 use translation, rotation, and stretching, and may be computed as

$$DX = XCT - CR \cdot (Y_2 + YCT) + XCS \cdot (X_2 + XCT)$$

$$DY = YCT + CR \cdot (X_2 + XCT) + YCS \cdot (Y_2 + YCT) \quad .$$

The corrected values of picture 2, registered to picture 1, are

$$X_2^{(c)} = X_2 + DX$$

$$Y_2^{(c)} = Y_2 + DY \quad .$$

This iterative process is intended to perform operations like those a human does in visually matching landmarks of one transparent cloud photograph to another; for example, using a light table or TV display device. However, we believe that the digital method is faster and more exact. A formal mathematical procedure to achieve the same results as this iterative technique could probably be formulated, perhaps using least-squares fitting methods; however, the results obtained iteratively appear to be satisfactory for present purposes, and we have not pursued this matter further.

VII PRELIMINARY ESTIMATE OF TIME AND COSTS

As mentioned earlier, the present computer programs require continued testing and improvement, and considerable changes are anticipated to improve their logic and their generality of application. Certain additional steps may be needed, and some present ones may be dropped. In spite of these uncertainties, we have made an estimate of the costs as presently envisioned.

A basic assumption in computing the costs of our system is that the data will be processed sequentially as 50 by 100 element arrays with each element corresponding to the brightness of a 5 by 5 mile area (approximately). In the 250 by 500 mile region covered by an array, about 10 cloud motion vectors will be found in a typical case. About 200 applications of the programs will be needed to cover the useful area of the earth's disk. Also, it is assumed that 10 landmarks will be matched on each pair of tapes. The amount of computer core storage needed will be 100 K octal (32,000) words or less. Approximately four hours of central processing time on a CDC 6400 computer would be required to process three pairs of tapes from a daily sequence. (It is possible that only two pairs would be needed in order to provide sufficient checks on consistency of motions.) This represents a cost per cloud motion vector equivalent to 2 to 3 seconds of CDC-6400 computer time. In an operational system such costs might amount to roughly 30 cents per vector. (At SRI, using an accounting algorithm for research programs the cost is approximately 2 to 3 times as large.) Major reductions in costs can be achieved by: improving the computer programs and hardware utilization; using a larger and faster computer; averaging the data to give larger elements; and, at SRI, using nighttime computing at a

special accounting rate. These computer costs are only about one-half (or less) than the estimated costs of present cloud motion determination by human operators (W. E. Evans, private communication, 1972).

VIII SUMMARY

The previous sections of this report describe a family of objective methods being developed to provide automatic determination of cloud motions from sequences of satellite pictures. A critical part of the concept is that of using the data in original coordinates, i.e., tape records (picture lines), and words within records. Transformations to earth coordinates are made last. This gives a large saving in computer processing time, since the transformations need be made only to the 10^3 to 10^4 cloud motion vectors obtained, and not to the 10^7 to 10^8 picture elements of an image. Also, serious inaccuracies in cloud motions that may be introduced by imprecise transformation of entire images are avoided. Landmark registration is done objectively, and the results are accurate to one picture element (i.e., approximately 2.5 miles). Higher accuracy can probably be obtained by averaging results from several nearby landmarks, and by including orbital and attitude information. In selected cases studied so far, the ISODATA and MOTION programs give results that appear very reasonable for single cloud layers having a rather uniform motion. However, the present methods do not cope adequately with complex motions of phenomena such as the ITCZ. We have formulated some additional concepts to handle such cases, and will test them in further work. One concept is to identify local centers that contrast with the nearby brightness, which may be relatively low or high. One way to find them would be to average the picture with a smoothing operator, and then take deviations from the average. Another possible method would use a grouping logic analogous to that of Duda and Blackmer (1972) for finding local centers. Finally, we have developed

a major part of a procedure for accurate transformation of cloud motions in tape coordinates to earth coordinates.

The accuracy of the cloud motion measurements depends on the accuracy achieved in the separate steps, and we have not yet determined the limitations on them. However, the results so far are believed to be acceptable according to usual meteorological standards.

The results which are accumulating give us confidence that objective determination of cloud motions for a wide variety of clouds in near real time will be feasible within approximately a year from the time of writing. Earlier in Section VII, a preliminary estimate of computer facilities needed and the approximate costs of cloud motion determination using these methods were given.

IX FURTHER RESEARCH

The work reported herein is intended to lead toward a procedure to be used operationally by the Fleet Numerical Weather Central, and also has application to the Global Atmospheric Research Program. A continuation of the work for possible use in GARP has been funded by the GARP Project office, Goddard Space Flight Center, NASA.

Further testing, improvement, and documentation of all of the computer programs is required. One of the principal tests of the objective procedures will be to compare them with visual operations based on the same data. It is necessary to determine the similarities and differences between computer results and visual tracking, especially for complex cloud masses. Such comparisons may lead to changes and improvements in the ISODATA and MOTION programs. The SRI electronic cloud console (Serebreny et al., 1970) will be used to perform these visual operations.

At present, information about the heights of clouds is lacking, and this greatly hampers cloud tracking by either computer or visual methods. This gap will be closed to a large extent by the SMS satellites which will obtain infrared measurements at approximately 11 μ. Our methods are intended to include the IR data (when they become available) as a simple addition to the variables used by ISODATA and MOTION. The manner in which IR data are used in determining cloud motions and assigning altitudes to them, and the additional costs of doing so, will be important in determining both the operational and research value of cloud motions.

An investigation is needed of the internal distortion in pictures (neglected so far) produced by certain varying orbital parameters, and of practical methods for correcting them. Probably such methods can be incorporated into the present program CORRECT.

Another subject that requires study is the objective analysis of cloud motions in combination with standard data and other satellite observations, for example, temperature profiles. Very probably the information found by ISODATA on the location, size, and changes in cloud groups could be related objectively to the fields of vorticity, divergence, and vertical motion.

It is worth noting that the methods being developed may have applications in tracking mixing ratio patterns on isentropic surfaces. As pointed out in a recent note (Endlich, Mancuso, and Nagle, 1972), observations of temperature and humidity profiles from geosynchronous satellites such as ATS-F may make such isentropic analyses possible at intervals of approximately an hour. If so, tracking humidity patterns to determine air motions in cloud-free regions may become feasible using automatic techniques such as those described in this report.

REFERENCES

Ball, G. H., and D. J. Hall, "A Clustering Technique for Summarizing Multivariate Data," Behavioral Science, Vol. 12, pp. 153-155 (1967).

Duda, R. D., and R. H. Blackmer, Jr., "Application of Pattern Recognition to Digitized Weather Radar Data," Final Report, Contract 1-36072, Stanford Research Institute, Menlo Park, Calif., 135 pp. (1972).

Endlich, R. M., D. E. Wolf, D. J. Hall, and A. E. Brain, "Use of a Pattern Recognition Technique for Determining Cloud Motions from Sequences of Satellite Photographs," J. Appl. Meteor., Vol. 10, No. 1, pp. 104-117 (1971).

Endlich, R. M., D. J. Hall, D. W. Wolf, and A. E. Brain, "Objective Methods for Registering Landmarks and Determining Cloud Motions from Satellite Data," FAMOS TR 8-71, Contract N62306-71-C-0068, Stanford Research Institute, Menlo Park, Calif., 40 pp. (1971).

Endlich, R. M., R. L. Mancuso, and R. E. Nagle, "A Proposed Method for Determining Winds in Cloud-Free Regions by Isentropic Analysis of Temperature and Water Vapor Profiles," to be published in J. Appl. Meteor.

Evans, W. E., and S. M. Serebreny, "Construction of ATS Cloud Console," Final Report, Contract NAS 5-11652, Stanford Research Institute, Menlo Park, Calif., 40 pp. (1969).

Fujita, T., K. Watanabe, and T. Izawa, "Formation and Structure of Anticyclones Caused by Large-Scale Cross Equatorial Flows Determined by ATS-1 Photographs," J. Appl. Meteor., Vol. 8, No. 4, pp. 649-667 (1969).

Hall, D. J., R. M. Endlich, D. E. Wolf, and A. E. Brain, "Objective Methods for Registering Landmarks and Determining Cloud Motions from Satellite Data," IEEE Trans. on Computor, Vol. C-21, No. 7, pp. 768-776 (1972).

Hubert, L. F., and L. F. Whitney, Jr., "Wind Estimation from Geostationary-Satellite Pictures," Mon. Wea. Review, Vol. 99, No. 9, pp 665-672 (1971).

Leese, J. A., C. S. Novak, and B. B. Clark, "An Automated Technique for Obtaining Cloud Motion from Geosynchronous Satellite Data Using Cross Correlation," J. Appl. Meteor., Vol. 10, No. 1, pp. 118-132 (1971).

Serebreny, S. M., E. J. Wiegman, R. G. Hadfield, and W. E. Evans, "Electronic System for Utilization of Satellite Cloud Pictures," Bull. Amer. Meteor. Soc., Vol. 51, No. 9, pp. 848-855 (1970).

Shenk, W. E., and E. R. Kriens, "A Comparison Between Observed Winds and Cloud Motions Derived from Satellite Infrared Measurements," J. Appl. Meteor., Vol. 9, No. 4, pp. 702-710 (1970).

Smith, E. A., and D. R. Phillips, "Automated Cloud Tracking Using Precisely Aligned Digital ATS Pictures," IEEE Trans. on Computers, Vol. C-21, No. 7, pp. 715-729 (1972).

User's Guide to ATS-I, Vol. 1. Prepared for NASA, Goddard Space Flight Center, by Allied Research Associates, Inc., Concord, Mass. (1967).